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RISK CHARACTERIZATION FROM MULTIPATHWAY EXPOSURE ASSOCIATED WITH LAND APPLYING
BIOSOLIDS BY ACCOUNTING FOR MULTIMEDIA MASS LOSS

by

Karthik Kumarasamy

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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2015

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ABSTRACT

Risk Characterization from Multipathway Exposure Associated with Land Applying Biosolids by
Accounting for Multimedia Mass Loss

by

Karthik Kumarasamy, Doctor of Philosophy

Utah State University, 2015

Major Professor: Dr. Michael J. McFarland
Department: Civil and Environmental Engineering

For over two decades the 40 CFR Part 503 has been the regulatory framework guiding land application of biosolids in the US. During this period public perception about the practice has worsened as evidenced by increases in partial and full biosolids land application bans across the US. In this work, the Multimedia, Multipathway and Multi-receptor Risk Assessment (3MRA) model was applied to four biosolids land application sites across the US (two sites in WA, one site each in VA and GA) to evaluate human health risk concerns from regulated (As and Cd) and non-regulated (B(a)P and DEHP) chemical constituents present in biosolids. The excess cancer risk from ingesting soil contaminated with As and Cd was higher than 1×10^{-6} when accounting for the background concentration. However, after separating the risk to reflect just the land application practice, the excess cancer risk estimates for the soil ingestion pathway were well below the acceptable risk criteria (several orders of magnitude lower). The non-cancer risk, for both As and Cd, was below 1. As and Cd remained mostly in the zone of biosolids incorporation. The combined As and Cd mass lost to all pathways for a 20-year consecutive application scenario was less than 15%. The classes of organic environmental toxins evaluated also did not cause

concern. Both B(a)P and DEHP aerobically degraded and less than 3% remained in the zone of biosolids incorporation after a 100-year consecutive biosolids application based on model predictions. Scenarios considering biosolids application at typical agricultural rates did not result in groundwater impairment for the sites evaluated; however, scenarios with biosolids applications that are similar to a surface disposal practice resulted in groundwater impairment. In addition to this work, sites across the US (in WA, VA and GA) were evaluated for groundwater impairment scenarios. The results from this effort clearly point towards no additional excess cancer ($>1 \times 10^{-6}$) or non-cancer ($HQ > 1$) health risks associated specifically with the practice of land application of biosolids for agricultural production for the sites and chemical contaminants evaluated.

PUBLIC ABSTRACT

Risk Characterization from Multipathway Exposure Associated with Land Applying Biosolids by
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Karthik Kumarasamy, Doctor of Philosophy

Utah State University, 2015

Major Professor: Dr. Michael J. McFarland
Department: Civil and Environmental Engineering

There continues to be concern among communities living in the vicinity of biosolids land application sites about potential adverse health effects from the chemical contaminants present in biosolids. This study describes a procedure that will help answer questions about the risks involved in biosolids land application at the site level, thus, this study will provide a crucial communication tool for wastewater treatment facilities and biosolids land appliers to address the concerns of the public. Specifically, the study quantifies the exposure concentrations that a human being can become exposed to during their lifetime from the practice. Crucially, it takes a quantitate approach to explain the risk associated with the practice of biosolids land application at the site level. From this modeling effort it can be concluded that biosolids do not present a cause for concern for the four chemical contaminants that were evaluated for a site in Yakima Valley, WA. Additionally, it was realized that a simple tool that only requires inputs that are currently being measured by the wastewater treatment plants or by land appliers can greatly aid stakeholders to get a sense of what is happening at a site. With this, the Biosolids and Groundwater Risk Characterization Tool (BGRST) was developed, which can be used by any

stakeholder and is designed to provide the non-cancer risk from drinking groundwater impaired by biosolids land application activities.

To Katherine

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process was long; however, I am thankful to so many people who played a role in shaping my thinking to where it is now.

Karthik Kumarasamy

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CHAPTER 1

INTRODUCTION

1.1. Background

Wastewater treatment results in the production of sewage sludge and is called biosolids when this sewage sludge is treated to comply with the requirements of 40 CFR Part 503 or similar such standard (NRC, 2002). Biosolids can be beneficially used to condition the soil or to fertilizer crops (Kelling et al., 1977; Khaleel et al., 1981; US EPA, 1992a; Andrés and Francisco, 2008; McIvor et al., 2012) because of its nutrient value and organic matter content (Naylor and Loehr, 1981; Guidi et al., 1983; Tsadilas et al., 1995; Rate et al., 2004). A common practice of land application involves incorporating biosolids to the soil (till zone) (US EPA, 1994) with approximately 60% of the 5.6 million dry tons of sewage sludge produced in the US being land applied (NRC, 2002; Paez-Rubio et al., 2006). Currently, approximately 0.1% of available agricultural land in US is being fertilized with biosolids (US EPA, 1996c; USDA, 1997). In addition to nutrients biosolids also introduce unwanted chemical pollutants to the soil (Epstein, 2002). Chemical constituents known to cause mutagenic, teratogenic, carcinogenic responses in human beings are commonly found in biosolids destined for land application (Kinney et al., 2006; US EPA, 2009). Consequently, there are increasing concerns about their use in an agricultural setting.

In 1993, the US EPA promulgated standards for the use or disposal of sewage sludge in the Code of Federal Regulations Title 40, Part 503 commonly referred as the Part 503 rule (US EPA, 1993). The Part 503 rule contains pollutant limits and management practices among other provisions to protect public health and the environment from any reasonably anticipated adverse effects from chemical and pathogenic pollutants (NRC, 2002). To establish the chemical pollutant limits, sewage sludge surveys and risk assessments were employed by the US EPA (US

EPA, 1982; US EPA, 1990; US EPA, 1992a; US EPA, 1992b). This effort by the EPA resulted in ceiling concentration and pollutant concentration limits among other restrictions for 9 inorganic chemical constituents present in biosolids (McFarland, 2001). Part 503 was envisioned to protect human health across wide geographic conditions that occur in the US and variations in biosolids characteristics (NRC, 2002). However, this national framework although conservative, fails to answer questions about actual risk from the practice at the site level.

During the twenty year period since the inception of Part 503, public perception about biosolids land application has largely remained unchanged (Renner, 2000; Bhandari and Xia, 2005; Harrison et al., 2006) as evidenced by increasing partial and full bans across the US (Beecher et al., 2004; WEF, 2011). Additionally, concerns among communities residing in the vicinity of a biosolids land application site have also not been completely addressed by Part 503 (Renner, 2000; NRC, 2002). There is also heightened distrust in the use of biosolids due to the presence of unknown constituents in biosolids (Citulski and Farahbakhsh, 2010). Further exacerbating the issue, the US EPA does not categorically assure the public that the practice is completely protective of human health and the environment (US EPA, 2000). This uncertainty highlights the need for a platform that can allow the characterization of risk at any land application site and also effectively communicate this risk.

Three areas of improvements to the Part 503 risk assessment are suggested in the National Research Council (NRC) report and includes: (1) incorporation of regional and site specificity in risk characterization, (2) include new and better models to simulate the fate and transport and (3) characterize aggregated risk in a multipathway setting from the land application practice (NRC, 2002). This study implements these suggested changes in characterizing the risk using data currently gathered by biosolids generating facilities and biosolids land appliers.

To accomplish these objectives, the Multimedia, Multipathway and Multi-receptor Risk Assessment (3MRA) model developed by US EPA was employed. 3MRA with modifications accounts for all the processes considered in Part 503 risk assessment in addition to other processes that were not included (e.g., irrigation water application and PM30 emissions). Although Part 503 has provisions to protect human health, the US EPA's Office of Inspector General audit concludes that "EPA does not have an effective program for ensuring compliance with the land application requirements of Part 503" (US EPA, 2000). Therefore, in order to evaluate risk from practices not allowed by Part 503, this study also evaluates scenarios such as non-agronomic rates and high contaminant loading rates (greater than ceiling concentration limits).

Four chemical constituents that ubiquitously occur in biosolids were identified for this study and are arsenic (As), cadmium (Cd), benzo [a] pyrene (B(a)P) and diethylhexyl phthalate (DEHP). As and Cd are currently regulated under Part 503 and were detected in 100% of all biosolids samples analyzed in the Targeted National Sewage Sludge Survey (TNSSS), whereas DEHP and B(a)P were detected in 100 and 77% of the samples, respectively (US EPA, 2009). As and Cd were selected for this work to serve as examples to determine if there is a need for reevaluation of currently regulated pollutants based on the 3MRA framework. On the other hand, B(a)P and DEHP were selected to ascertain the need for including currently non-regulated chemical pollutants. In addition, B(a)P and DEHP were considered for this work as they were included in Part 503 risk assessments, but were excluded from the final regulation as they were deemed as not a cause for concern. Hence, the authors wanted to determine if the new approach resulted in differences in outcomes.

1.2. Objectives of this Study

The objectives of this study are to incorporate computational tools and data that have become available subsequent to the promulgation of Part 503 to assess the public health risks associated with land applying biosolids. This study employs the 3MRA model and capitalizes on the model's ability to determine both cancer and non-cancer risk from biosolids land application practice in a multimedia and multipathway setting at the site level. Consequently, it is anticipated that this effort will aid a stakeholder to (1) ascertain and (2) effectively communicate the risk resulting from the practice at the site level. To this regard, this work specifically addresses the following topics:

1. Site specific assessment of human health risk from land applied biosolids by quantifying contaminant mass lost to different pathways in a multimedia setting.
2. Assess cancer risk and hazard quotient to a human receptor living in the vicinity of the site.
3. Apply modified 3MRA model by including processes that were not accounted in Part 503 rule and the regulatory reviews that were conducted thereafter.
4. Develop a screening tool to characterize the non-cancer risk from ingesting groundwater impaired from the practice primarily targeting POTWs.
5. Modify the 3MRA model to better characterize agricultural practices typical to a biosolids land application facility and compare with measured data.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The benefits of biosolids land application to agricultural land are well documented in the literature (Logan and Harrison, 1995; Zebarth et al., 1999) with examples that include increased crop yields and improved soil properties (Cogger et al., 2001; Mantovi et al., 2005; McFarland et al., 2008). In the US, biosolids beneficial use programs have to meet at the very least the federal regulatory requirements contained in Part 503 promulgated in 1993 and the amendments of 1994 and 1995 (US EPA, 1993; US EPA, 1994; US EPA, 2006). This rule is intended to protect the public health from any potential adverse health effects that may result from the practice (US EPA, 1994). However, concerns about its protectiveness have continued to persist during the two decades since its promulgation (McBride, 1995; La Guardia et al., 2001). Although no clear scientific evidence on adverse health effects resulting from the adoption of Part 503 exists, there clearly is a need for addressing the persistent uncertainty associated with the land application practice (NRC, 2002; Schoof and Houkal, 2005). This review of the literature is structured to describe the Part 503 rule, the risk assessment that shaped this regulation, the pollutants selected for the study and the 3MRA model.

2.2. 40 Code of Federal Regulations Part 503

The Part 503 rule prescribes an approach that is national in scope with several layers of conservative assumptions incorporated into the ruling to account for a reasonable worst case scenario (US EPA, 1992a; US EPA, 1992b). Nine inorganic chemical constituents present in biosolids are currently regulated in land applied biosolids (US EPA, 1994; NRC, 2002). Part 503 lists “Ceiling Concentration” limits for all land applied biosolids and “Pollutant Concentration”

limits for “Exceptional Quality” (EQ) and “Pollutant Concentration” (PC) biosolids (see Table 1).

The ceiling concentration limits determines the suitability of biosolids for land application and were established based on the 1988 National Sewage Sludge Survey (NSSS) (US EPA, 1990). On the other hand, the pollutant concentration limits were established based on a risk assessment (US EPA, 1992a; US EPA, 1992b). Hence, a study that assess the risk from applying biosolids at ceiling concentration is needed.

As part of the risk assessment As, Cd, B(a)P and DEHP were assessed by the US EPA and were considered based on frequency of occurrence, aquatic toxicity, phytotoxicity, human health effects, domestic and wildlife effects and plant uptake (US EPA, 1992a; US EPA, 1992b). The metals evaluated in the Part 503 risk assessment are assumed not to reach an equilibrium and hence, their concentration in the soil will continue to rise with repeat applications. On the other hand, organic pollutants such as DEHP and B(a)P are assumed even in the worst case scenario to only potentially reach steady state, thus leading to no loading rate stipulations in the final rule (US EPA, 1992b). The four competing mass loss processes accounted for in Part 503 are erosion, leaching, volatilization and biodegradation (US EPA, 1992b). The assumptions made

Table 1. Ceiling and pollutant concentration limits from Part 503*

Pollutant	Ceiling concentration limits for all biosolids land applied (mg/kg)**	Pollutant concentration limits for EQ and PC biosolids (mg/kg)**
Arsenic	75	41
Cadmium	85	39
Copper	4300	1500
Lead	840	300
Mercury	57	17
Molybdenum	75	-
Nickel	420	420
Selenium	100	36
Zinc	7500	2800

* Part 503 section 503.13 Table 1 and Table 3

** Dry weight basis

in Part 503 that are relevant to this modeling effort are listed in Table 2. Additionally, fourteen routes of exposures (pathways) were evaluated for biosolids applied to agricultural land (Table 3) as part of the Part 503 risk assessment (US EPA, 1992a; NRC, 2002). As, Cd and B(a)P were assessed for Pathways 1 through 10, B(a)P and DEHP for pathway 13, As and Cd for pathway 11 and all four of the chemical constituents were assessed for pathways 12 and 14 (US EPA, 1992a). The risk assessments that have led to the development of the Part 503 chemical pollutant standards were conducted more than two decades ago at a conservative setting to represent the entire US. With advances in modeling exposure and significant changes in risk assessment methodologies, the NRC committee recommends site specific assessment of risk (NRC, 2002). In addition, biosolids constituents that are currently unregulated could become regulated pollutants following the US EPA biennial review (a process that is mandated by the Clean Water Act Title 33 Section 405) (US EPA, 2006; US EPA, 2008; US EPA, 2012).

The Part 503 assumptions (listed in Table 2) are meant to capture wide variability in soil types, geology and agricultural practices occurring in the US to account for the reasonable worst case scenario. However, this approach can under or overestimate risk from any particular

Table 2. Parameter assumptions in Part 503 exposure and risk assessment (US EPA, 1992b)

Parameter	Value
Sludge Management Area (ha)	1074
Watershed Area (ha)	440330
Depth of incorporation of sewage sludge (m)	0.15
Lateral distance to well (m)	0
Width of buffer zone (m)	10
Wind velocity (m/sec)	4.5
Average air temperature (°K)	288
Number of applications of sewage sludge (unitless)	20
Yearly loss to soil erosion (m/year)	0.00060
Depth to groundwater (m)	1.0
Net recharge or seepage (m/year)	0.5
Saturated hydraulic conductivity of the soil (m/hr)	0.61
Soil type	sand

Table 3. Fourteen exposure pathways assessed as part of the risk assessment for Part 503

Pathway Number	Pathway	Description of Highly Exposed Individual (HEI)
1	Sewage sludge → Soil → Plant → Human	Human ingesting plants grown in sewage sludge.
2	Sewage sludge → Soil → Plant → Human	Residential home gardener.
3	Sewage sludge → Soil → Human	Children ingesting sewage sludge.
4	Sewage sludge → Soil → Plant → Animal → Human	Farm households producing a major portion of the animal products they consume. It is assumed that the animals eat plants grown in soil amended with sewage sludge.
5	Sewage sludge → Soil → Animal → Human	Farm households consuming livestock that ingest sewage sludge while grazing.
6	Sewage sludge → Soil → Plant → Animal	Livestock ingesting crops grown on sewage sludge amended soil.
7	Sewage sludge → Soil → Animal	Grazing livestock ingesting sewage sludge.
8	Sewage sludge → Soil → Plant	Plants grown in sewage sludge amended soil.
9	Sewage sludge → Soil → Soil organism	Soil organism living in sewage sludge amended soil.
10	Sewage sludge → Soil → Soil organism → Predator	Animals eating soil organisms living in sewage sludge amended soil.
11	Sewage sludge → Soil → Airborne dust → Human	Tractor operator exposed to dust while plowing large areas of sewage sludge amended soil.
12	Sewage sludge → Soil → Surface water → Human	Water quality Criteria for receiving water for a person who consumes 0.04 kg/day of fish and 2 l/day of water.
13	Sewage sludge → Soil → Air → Human	Human breathing volatile pollutants from sewage sludge.
14	Sewage sludge → Soil → Groundwater → Human	Human drinking water from wells contaminated with pollutants leaching from sewage sludge amended soil to groundwater.

pathway. For example, a biosolids land application site with shallow groundwater table (the assumed 1.0 m in Part 503) might constitute a risk primarily from the consumption of impaired untreated groundwater. Nonetheless, at a site with deeper depth to water table and lower hydraulic conductivities the risk from the pathway could essentially be nonexistent. It is therefore necessary to consider site conditions in the risk assessment rather than adopting a generic site approach.

2.3. Pollutants of Concern (POC) for Multimedia Mass Loss Risk Assessment

Three classes of environmental toxins are evaluated in this study: heavy metals, phthalates and polycyclic aromatic hydrocarbons (PAHs) (Manzetti et al., 2014). Among the heavy metals As and Cd were selected, among the phthalates DEHP was selected and among the PAHs B(a)P was chosen. All four of the chemical constituents As, Cd, B(a)P and DEHP evaluated in this study are listed in the 2013 priority list of hazardous substances (ATSDR, 2014). In addition they were also detected at 100% for all biosolids samples analyzed except for B(a)P which was detected at 77.1% (US EPA, 2009).

2.3.1. Arsenic

Arsenic is naturally present in the environment constituting the 12th most abundant element in the earth crust (Bissen and Frimmel, 2003) but is also introduced from anthropogenic activities (Mandal and Suzuki, 2002). In air it is primarily adsorbed to particulate matter (Davidson et al., 1985) and is found in very low concentrations in natural waters (Mandal and Suzuki, 2002). Arsenic uptake by plants is almost solely a function of the exposure concentration for the plant (Bissen and Frimmel, 2003) with As distribution among plant parts highly variable (Peryea, 2001). Commercial arsenic applications include herbicides (Sachs and Michael, 1971), insecticides, desiccants and wood preservatives (Hingston et al., 2001) and even as feed

additives (Chapman and Johnson, 2002; Lasky et al., 2004; Wallinga, 2006) and drugs (Gorby, 1994; Ohnishi et al., 2002).

The chronic toxicity effects resulting from drinking water impaired with inorganic As includes skin lesions, hyperpigmentation and is also known to affect cardiovascular, gastrointestinal and urinary systems (Kapaj et al., 2006). Arsenic is known to cause both cancer and non-cancer effects in human beings (Water, 1999). Arsenic is associated with cancers such as skin, bladder and lung (Chen et al., 2004; Luster and Simeonova, 2004; Rossman et al., 2004). The current drinking water standard (Maximum Contaminant Limit (MCL)) for As set by the US EPA is 0.01mg/l whereas the Maximum Contaminant Limit Goal (MCLG) is zero (US EPA, 2001). Exposures through inhalation of arsenic containing particulate matter is also a cause for concern (Zheng et al., 1996).

Arsenic was detected in 100% of all biosolids samples analyzed in TNSSS and its concentration ranged between 1.18 and 49.2 mg/kg (US EPA, 2009) and could potentially limit the use of biosolids if present in high quantities (US EPA, 1993; Ascar et al., 2008b). Although, As fate and behavior in soils systems is dependent on its chemical form, the predominantly stable species is As(V) under aerobic conditions. As (III), on the other hand, the most mobile is present in neutral form as H_3AsO_3 (Ascar et al., 2008a). Soil/biosolids-solution (water) coefficients are used in modeling the transport of As.

2.3.2. Cadmium

Cadmium sources to a municipal wastewater treatment plant could originate from: households (the amount of cadmium in urine and feces), industries (electroplating, iron and steel production, lead smelter, fuel combustion, car washing, leachate from landfills) and storm water (Lindqvist-Östblom and Eklund, 2001). Adverse health effects resulting from chronic

exposure to Cd includes: renal effects such as increased albumin in urine and decreased glomerular filtration rate (Roels et al., 1999; Järup et al., 2000), respiratory effects such as lung cancer (Sorahan and Esmen, 2004), cardiovascular effects such as peripheral artery diseases (Navas-Acien et al., 2004; Navas-Acien et al., 2005) and skeletal lesions (Nogawa et al., 2004). Symptoms such as severe osteoporosis, osteomalacia among others are characteristic of the “Itai-Itai” or ouch-ouch disease and is attributed to Cd (Nogawa et al., 1975; Kasuya et al., 1992).

The variability of organic matter breakdown, its contribution to metal release and time of release (Hooda and Alloway, 1994) from the soil-biosolids matrix all contribute to uncertainty in the K_D value estimates (Brown et al., 1998). Variability in K_D for Cd are listed in Table 4. Biosolids compositional factors further complicate the release of metals with sewage sludge as old as five years continuing to decompose and releasing metals to plant available pools (Stacey

Table 4. K_D values for As and Cd

Chemical constituent	K_D (L kg ⁻¹)	Description	Source
Cd	2500	Orchard sludge site	(McBride et al., 1997)
	161±7	50% sludge/soil mixture	
	139±8	20% sludge/soil mixture	
	0.009 – 97.2	pH 4.5 – pH 6.5 Metal salts were used in sludge supernatant solution	(Gao et al., 1997)
	690 – 2010	pH 7.37 – pH 8.44	(Merrington and Smernik, 2004)
As	0.44 – 192000	Number of data points = 830	(Sauvé et al., 2000)
	1.6 – 530000	Number of data points = 66	(Sauvé et al., 2000)
	0.3 – 4.3	Soil/Water Number of data points = 22	(Allison and Allison, 2005)
	2.0 – 6.0	Suspended sediment matter/ water Number of data points = 25	
	1.6 – 4.3	Sediment/ water Number of data points = 18	

et al., 2001). Cd was detected in 100% of all biosolids samples analyzed in TNSSS and ranged between 0.21 and 11.8 mg/kg (US EPA, 2009).

2.3.3. Benzo [a] Pyrene

Benzo [a] pyrene is a hydrophobic ($\log K_{ow} = 6.11$) (US EPA, 1996b) polycyclic aromatic hydrocarbon (PAH) that is classified as a probable human carcinogen (US EPA, 1978) and is formed from incomplete combustion of organic matter (e.g., automobile exhaust, municipal refuse incinerators and coal combustion (Lee et al., 1995; Colmsjö et al., 1986; Mastral et al., 2001; Khalili et al., 1995; Cai et al., 2007)). Environmentally relevant properties are listed in Table 5. The chemical formula for B(a)P is $C_{20}H_{12}$ and is sorbed to particles present in the air at ambient temperatures (Ravindra et al., 2008). Atmospheric dusts, oils and greases and road-wear particles are transported to the wastewater treatment plant by street runoff and is suspected to be source of B(a)P (Pham and Proulx, 1997). Low aqueous solubility of B(a)P results in its removal from water and its transfer to the sludge during the wastewater treatment process (Rogers, 1996; Jiries et al., 2000; Harrison et al., 2006). B(a)P was detected in 77.1% of all biosolids samples analyzed in TNSSS and ranged between 63 and 4500 $\mu\text{g/kg}$ (US EPA, 2009).

2.3.4. Diethylhexyl Phthalate

Phthalates are used in many products such as plastics, lubricating oils, solvents and detergents (Blount et al., 2000) and have been associated with reproductive disorders (Duty et al., 2004). Diethylhexyl phthalate (DEHP) is a antiandrogenic endocrine disrupting compound (EDC) (Parks et al., 2000) ubiquitous in biosolids (Madsen et al., 1999; Kinney et al., 2006). Among phthalate esters, DEHP is one of the most widely used phthalates which is attributed to its stability and low volatility (Stales et al., 1997) with annual global production estimated at

Table 5. Environmentally relevant properties for B(a)P and DEHP (US EPA, 1996b)

Compound	Solubility $\left(\frac{mg}{L}\right)$	HLC $\left(\frac{atm - m^3}{mol}\right)$	H' (dimensionless)	Log K _{ow}
Benzo(a)pyrene	1.62E-03	1.13E-06	4.63E-05	6.11
Bis(2-ethylhexyl)phthalate	3.40E-01	1.02E-07	4.18E-06	7.30

HLC – Henry's law constant, H' – Dimensionless Henry's law constant.

1-20 × 10⁶ tons (Schmitzer et al., 1988). The chemical formula for DEHP is C₂₄H₃₈O₄ with specific gravity of 0.986 at 20°C (Howard et al., 1985). DEHP added as a plasticizer to poly (vinyl chloride) (PVC) plastics to increase flexibility is known to leach as it is loosely attached to the parent matrix (Rock et al., 1986). DEHP is listed as a priority pollutant by the US EPA and other state environment protection agencies (Xu et al., 2008). DEHP is also most resistant to microbial degradation among the phthalate esters (Rogers, 1996). DEHP was detected in 100% of all biosolids samples analyzed in TNSSS and ranged between 654 and 310000 µg/kg (US EPA, 2009). Environmentally relevant properties are listed in Table 5.

2.4. Multimedia, Multipathway and Multi-receptor Risk Assessment (3MRA) Model

3MRA is a process-based model with 18 modules that evaluates fate and transport of chemical contaminants in a multimedia, multipathway setting (US EPA, 1999d). It is able to predict contaminant fate, transport and its eventual exposure to a human receptor residing in the vicinity of a land application site called Area of Interest (AOI). The AOI is defined as the region 2000 m from the boundary of the site. Finally, it is also able to characterize the risk from the estimated exposure concentrations. Figure 1 shows the modules relevant to this study and their connectivity within the modified 3MRA model. The Land Application Unit (LAU) generates outputs which are used by environmental fate and transport and exposure and risk modules to

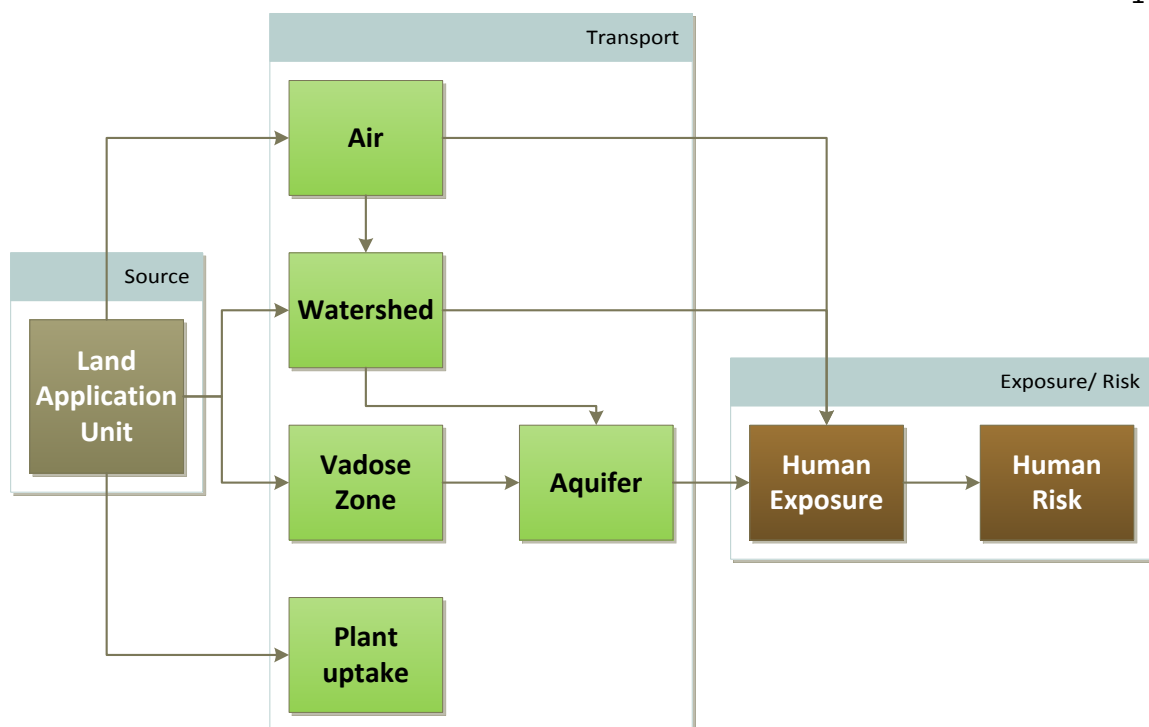


Figure 1. Connectivity among the source, transport, exposure and risk modules used in this work.

estimate cancer or non-cancer risk to human or ecological receptors (US EPA, 1999m). Plant uptake is part of the modified version of the model and is not included in the original (base) model. The outputs from the LAU are used to estimate annual average air concentration of chemical constituents at receptor locations within the area of interest.

Industrial Source Complex-Short Term (ISCST3) is used for modeling chemical pollutants assumed to be in the form of either volatilized gases or as fugitive dust that are emitted from the LAU. ISCST3 is employed in its legacy form with pre and post processors to connect with the rest of the 3MRA framework (US EPA, 1999a). The watershed module is linked to the LAU and is a dynamic, two-dimensional model that is capable of simulating fate and transport within watershed “subareas” that are hydrologically linked (US EPA, 1999o). The vadose zone and aquifer portion of the contaminant fate and transport is simulated within the 3RMA framework

using US EPA's Composite Model for leachate migration with Transformation Products (EPACMTP) and simulates: (1) advection, (2) hydrodynamic dispersion, (3) linear or nonlinear sorption, (3) branch decay and (4) chain-decay reactions (US EPA, 1999n). The human exposure module estimates the applied dose for the chemical constituent to human receptors from the media modules of 3MRA (US EPA, 1999b). The human risk module calculates the cancer risk or non-cancer risk to human receptors based on cohort, exposure pathway, exposure area and year (US EPA, 1999c). Sections 2.4.1 to 2.4.6 describes the LAU in detail.

2.4.1. Biosolids Land Application Practice

Within the 3MRA computational framework, the pollutant mass flux rates are computed in a multimedia setting from the biosolids land application site using the Land Application Unit (LAU) module. The LAU module invokes the Combined Local Watershed and Generic Soil Column Module (GSCM). The contaminant is modeled in a two-dimensional, two-medium system with soil column being one medium and during runoff events the overlying runoff layer as another medium. The local watershed is the drainage area containing only the site and the upstream and downstream areas. In other words, it is just the areas that are in the lateral direction to runoff flow as shown in Figure 2. The flow in the local watershed is assumed to be sheet flow only. A description of GSCM followed by integration of the local watershed module with GSCM is presented in the following paragraphs.

The LAU module is used to estimate annual average constituent surface soil concentration as well as the constituent mass emission rates to air and groundwater. The LAU module is integrated with environmental fate and transport modules that use the estimates to further propagate the contaminant to compute the exposure concentration. GSCM describes the dynamics of a chemical constituent in near surface soils. Soil is defined as the medium

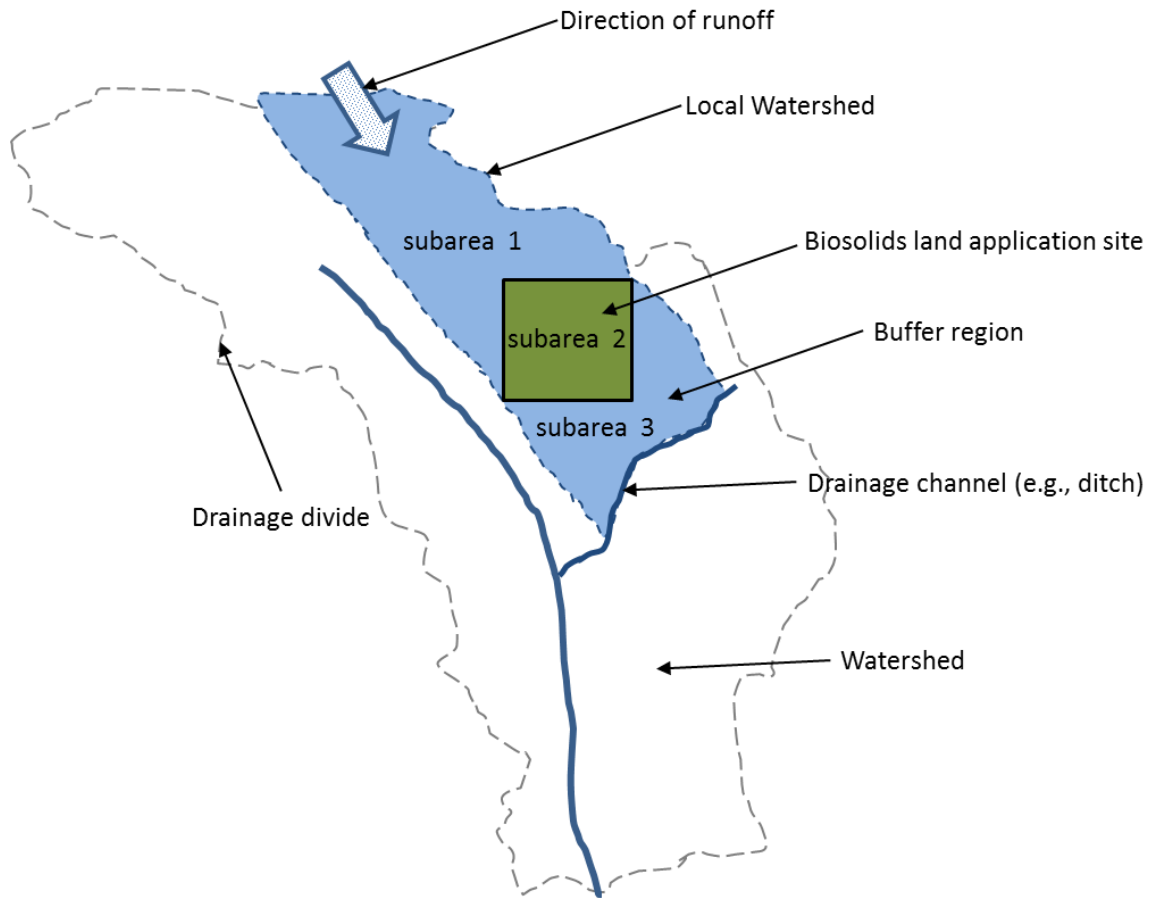


Figure 2. Conceptual schematic of a local watershed. There are three subareas, namely; upstream region, biosolids land application site and downstream buffer strip. The downstream buffer strip is defined as the region between the site and the downstream drainage divide (e.g., like a stream, lake or some waterbody). Part 503 considered a 10 m set back distance during the risk assessment.

consisting of a homogenous mixture of soil and biosolids in the site and just soil in other watershed subareas. In the following paragraphs, governing equation, quasi-analytical solution, boundary conditions, processes simulated and the assumptions are all described in the context of biosolids land application practice. Information gathered from the national survey is used to model the Best Management Practices (BMPs) commonly employed by the biosolids industry. This approach can capture the practice and aid in the allocation of resources for contaminant mitigation efforts.

A biosolids land application practice is modeled accounting for periodic addition of Pollutants of Concern (POC) and the pollutant mass loss to processes such as runoff, water erosion, wind erosion and plant uptake. Mechanisms through which pollutant mass may be lost are: (1) through volatilization of a chemical constituent in gas phase to the atmosphere or the air compartment and (2) leaching of the chemical constituent by advection and diffusion. The first order mass loss processes include: (1) abiotic and biotic degradation, (2) suspension of chemical constituent sorbed to surface particles due to wind and water erosion and vehicular activity and (3) surface runoff of dissolved chemical constituents. Chemical constituents are modeled for addition and removal to simulate an active biosolids land application site. Constituent addition implies a biosolids land application event and removal indicates transport of the constituent to other media or degradation. A constituent mass balance is maintained throughout the multimedia setting.

2.4.2. GSCM Assumptions

The following is a list of assumptions that are described in the context of biosolids land application practice:

1. A chemical constituent partitions into sorbed, dissolved and gaseous phase as described in Equation (1).

$$C_T = \rho_b C_S + \theta_w C_L + \theta_a C_G \quad (1)$$

where

C_T = total contaminant concentration in biosolids soil mixture $\left(\frac{g}{m^3}\right)$

ρ_b = soil dry bulk density $\left(\frac{g}{cm^3}\right)$

C_S = sorbed phase contaminant concentration in biosolids soil mixture $\left(\frac{\mu g}{g}\right)$

θ_w = volumetric water content in the biosolids soil mixture $\left(\frac{m^3 \text{ of soil water}}{m^3 \text{ of soil}} \right)$

C_L = aqueous phase contaminant concentration $\left(\frac{g}{m^3 \text{ of soil water}} \right)$

θ_a = volumetric air content in the biosolids soil mixture $\left(\frac{m^3 \text{ of soil air}}{m^3 \text{ of soil}} \right)$

C_G = gas phase contaminant concentration $\left(\frac{g}{m^3 \text{ of soil air}} \right)$

Phase partitioning between sorbed and liquid phases is linear and reversible and is given as in Equation (2). For organic contaminants K_d is defined as in Equation (3) and for inorganic contaminants K_d is given as input.

$$C_S = K_d C_L \quad (2)$$

where

K_d = linear equilibrium partitioning coefficient $\left(\frac{cm^3}{g} \right)$

$$K_d = f_{oc} \cdot K_{oc} \quad (3)$$

where

f_{oc} = organic carbon fraction in soil (dimensionless)

K_{oc} = equilibrium partition coefficient normalized to organic carbon (dimensionless)

2. Partitioning of the chemical constituent between dissolved and gaseous phases is assumed to follow Henry's law and is given as in Equation (4). C'_T can also be expressed as written as shown in Equation (5).

$$C_G = H' C_L \quad (4)$$

where

H' = Henry's law coefficient (dimensionless)

$$C'_T = \frac{C_T}{\rho_b} \quad (5)$$

where

C'_T = total contaminant concentration expressed as contaminant mass per unit of dry soil

C_T can also be expressed in terms of C_T , C_s , C_G as shown in Equations (6), (7) and (8), respectively.

$$C_T = K_{TL} C_L \quad (6)$$

$$C_T = \frac{K_{TL}}{K_d} C_s \quad (7)$$

$$C_T = \frac{K_{TL}}{H'} C_G \quad (8)$$

Where K_{TL} is defined as the equilibrium distribution coefficient between total and aqueous phase chemical constituent concentration and is shown as in Equation (9).

$$K_{TL} = \rho_b K_d + \theta_w + \theta_a H' \quad (9)$$

3. A chemical constituent is transported in one-dimension through the soil column with the volume of the soil column remaining constant and position is fixed with respect to the water table.

2.4.3. Governing Mass Balance Equation

The contaminant mass fate and transport at the biosolids land application site is

modeled by accounting for diffusive, convective and decay components as shown in Equation (10).

$$\frac{\partial C_T}{\partial t} = D_E \frac{\partial^2 C_T}{\partial z^2} - V_E \frac{\partial C_T}{\partial z} - k C_T \quad (10)$$

where

k = total first order loss rate $\left(\frac{1}{d}\right)$

D_E = effective diffusivity $\left(\frac{m^2}{d}\right)$. See Equation (11).

V_E = effective solute convection velocity $\left(\frac{m}{d}\right)$ and is defined as in Equation (12).

z = downward direction in the soil column

t = time

$$D_E = \frac{\left(\theta_a^{\frac{10}{3}} D_a H' + \theta_w^{\frac{10}{3}} D_w \right) 8.64}{\eta^2 K_{TL}} \quad (11)$$

$$V_E = \frac{I}{K_{TL}} \quad (12)$$

where

8.64 = conversion factor $\left(\frac{m^2 s}{cm^2 d}\right)$

D_a = air diffusivity $\left(\frac{cm^2}{s}\right)$

D_w = water diffusivity $\left(\frac{cm^2}{s}\right)$

η = porosity

2.4.4. GSCM Solution Technique

The diffusive, convective and decay components of the governing equation are solved using a quasi-analytical solution technique. In other words, the solution is obtained by superposition of the solutions of the three individual components on the same grid. The individual solutions are combined to obtain a pure diffusion solution that moves with a velocity and decays exponentially with time (US EPA, 1999m). The modeled soil column is divided into layers with a layer depth of dz . The $D_E \frac{\partial^2 C_T}{\partial z^2}$ (diffusive component) of Equation (10) has one-dimensional solution as given in Equation (13) for a layer of width dz and centered at $z' = 0$.

$$C_T(z', t) = \frac{C_{T0}}{2} \left[\operatorname{erf} \left(\frac{z' + \frac{dz}{2}}{\sqrt{4D_E t}} \right) + \operatorname{erf} \left(\frac{\frac{dz}{2} - z'}{\sqrt{4D_E t}} \right) \right] \quad (13)$$

The total mass of chemical constituent that has passed z' after time t is calculated as shown in Equation (14) which can be further simplified as shown in Equation (15).

$$m(z', t) = 2 \int_{z'}^{\infty} C_T(z, t) dz \quad (14)$$

$$m(z', t) = C_{T0} \sqrt{4D_E t} \left[\int_{\frac{(z' - \frac{dz}{2})}{\sqrt{4D_E t}}}^{\infty} \operatorname{erfc}(y) dy - \int_{\frac{(z' + \frac{dz}{2})}{\sqrt{4D_E t}}}^{\infty} \operatorname{erfc}(y) dy \right] \quad (15)$$

The integral is evaluated as shown in Equation (16) (Abramowitz and Stegun, 1970).

$$\int \operatorname{erfc}(x) dx = x \times \operatorname{erfc}(x) - \frac{1}{\sqrt{\pi}} \exp(-x^2) + \text{constant} \quad (16)$$

The fraction of the mass that diffuses past a boundary, in other words, across either the upper or the lower boundary layer in time 0 to t is given by Equation (17) and the amount that remains within the layer is given by Equation (18).

$$Df(z', t) = 0.5 \frac{\sqrt{4D_E t}}{dz} \left[\int_{\frac{(z' - \frac{dz}{2})}{\sqrt{4D_E t}}}^{\infty} \operatorname{erfc}(y) dy \right. \quad (17)$$

$$\left. - \int_{\frac{(z' + \frac{dz}{2})}{\sqrt{4D_E t}}}^{\infty} \operatorname{erfc}(y) dy \right]$$

$$Df_0(t) = 1 - 2 Df(z' = 0.5dz, t) \quad (18)$$

where

$Df(z', t)$ = fraction of mass that moves past the boundary by diffusion

$Df_0(t)$ = fraction of mass remaining in the layer during the time period after diffusion has occurred in the time period 0 to t

The total diffusive mass loss across the lower boundary of the soil column can be calculated as the sum of the diffusive mass from all layers of the soil column. This includes both aqueous and gaseous phase diffusive flux. Likewise, the mass of chemical constituent lost through the upper boundary through diffusion is obtained by accounting only for the gaseous phase diffusive flux as shown in Equation (19). The volatilization loss from the surface is assumed

to be only due to gaseous phase diffusion. The mass that is lost in the model is added back into the surface layer to maintain the mass balance and is calculated as shown in Equation (20).

$$M_{vol}(t) = M_0(t) \frac{D_{E,a}}{D_E} \quad (19)$$

$$M_{added\ back}(t) = M_0(t) \frac{D_{E,w}}{D_E} \quad (20)$$

The decay component of the governing equation given in Equation (10) has the solution of the form shown in Equation (21). The mass lost can be calculated for any time t using Equation (22). The mass lost due to any first order mass loss process j can be calculated using Equation (23). To avoid the generation of an artificial numerical diffusion associated with the layered solution the components of each layer are transferred to the next layer at the end of each time step. The time step is calculated as given in Equation (24).

$$C_T = C_{T0} \exp(-kt) \quad (21)$$

$$M_{loss}(t) = (1 - \exp(-kt)) C_{T0} dz \quad (22)$$

$$M_{loss,j}(t) = \frac{k_j}{k} M_{loss}(t) \quad (23)$$

$$dt = \frac{dz}{V_E} \quad (24)$$

2.4.5. Boundary Conditions

Air compartment above the soil column is assumed to be a sink and hence a zero concentration boundary condition is assumed for the upper boundary. A zero gradient boundary condition is assumed for the lower boundary condition. The Boundary Condition Multiplier (bcm) is set to one for this case. A reflection of the soil column is created where the reflected soil column layer cells are set with a concentration of bcm times the contaminant concentration

in the column being reflected. In other words, this is the case of no diffusion boundary condition, meaning the reflected column completely offsets the diffusive flux out of the lower boundary of the soil column.

2.4.6. Land Application Unit (LAU) Assumptions

Multimedia mass loss from biosolids land application practice is simulated using the LAU module of 3MRA. LAU module of 3MRA consists of the local watershed and soil column modules (see Figure 3), which are both executed in an integrated way to account for the mass lost in a multimedia setting. The processes simulated and assumptions common to both the local watershed module and the soil column modules are listed below:

1. Biosolids are applied to the soil surface periodically at even intervals followed by tilling to create a homogenous soil-biosolids layer in the till zone during the sites operational years, $y_{op}(yrs)$.
2. Limited by the root zone's saturated hydraulic conductivity, the annual average leachate infiltration rate, $I \left(\frac{m}{d} \right)$ is calculated as shown in Equation (25). In other words, soil moisture, $SM (cm)$ in the till zone that is not used to satisfy evapotranspiration, $ET \left(\frac{cm}{d} \right)$ and which is in excess of field capacity, $FC (cm)$ is considered as available for drainage (Dunne and Leopold, 1978). To preserve the mass balance, when infiltration is limited by $K_{sat} \left(\frac{cm}{d} \right)$ the additional moisture is added to the runoff as runoff depth, $RO (cm)$. ET and RO are calculated as shown in Equations (26) and (32), respectively. RO is calculated based on Soil Conservation Service (SCS) Curve Number procedure. RO is a function of current and antecedent precipitation and land use (USDA, 1986).

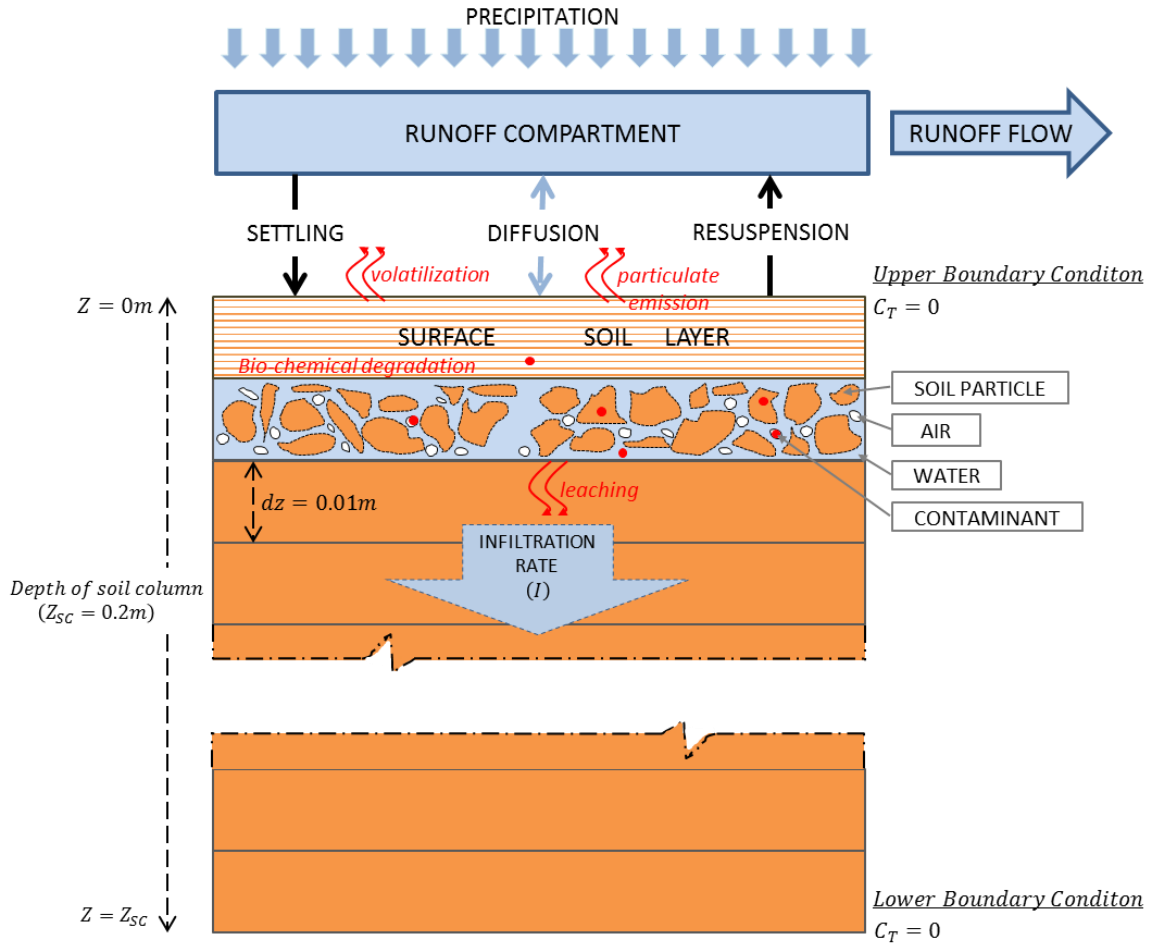


Figure 3. General Soil Column Model (GSCM).

$$I = \min \left\{ \frac{K_{sat}}{100}, (SM - FC) \frac{DRZ}{1 \times 10^4} \right\} \quad (25)$$

where

K_{sat} = saturated hydraulic conductivity $\left(\frac{cm}{d} \right)$

SM = soil moisture in the till zone (cm)

FC = field capacity in the till zone (cm)

DRZ = depth of root zone (cm)

$$ET = \min \left\{ PET, PET \left(\frac{SM - WP}{FC - WP} \right) \right\} \quad (26)$$

where

PET = Potential Evapotranspiration $\left(\frac{cm}{d} \right)$ calculated using Hargreaves Equations as shown in Equation (27).

WP = wilting point in the till zone (cm)

$$PET = 0.0023 S_o \Delta_T^{0.5} (T + 17.8) 0.1 \quad (27)$$

where

S_o = water equivalent of extraterrestrial radiation $\left(\frac{mm}{d} \right)$ and can be calculated as shown in Equation (28).

Δ_T = difference in maximum average monthly temperature and the minimum average monthly air temperature

T = average daily air temperature ($^{\circ}C$)

$$S_o = 15.392 d_r (\varpi_s \sin \phi \sin \theta + \cos \phi \cos \theta \sin \varpi_s) \quad (28)$$

where

ϖ_s = sunset hour angle ($radians$) and is calculated as shown in Equation (30).

d_r = calculated as shown in Equation (31).

ϕ = biosolids land application site latitude with positive for the northern and negative for south hemispheres, respectively.

θ = solar declination ($radians$) and is calculated as shown in Equation (29).

$$\theta = 0.4093 \sin \left(\frac{2\pi}{365} J - 1.405 \right) \quad (29)$$

$$\varpi_s = \cos^{-1}(-\tan \phi \tan \theta) \quad (30)$$

$$d_r = 1 + 0.033 \cos \left(\frac{2\pi}{365} J \right) \quad (31)$$

where

J = Julian day

$$RO = \begin{cases} \frac{(P - Ia)^2}{P - Ia + S}, & P \geq Ia \\ 0, & P < Ia \end{cases} \quad (32)$$

where

P = sum of precipitation and irrigation water depth (cm). Irrigation water is added only during the growing season

Ia = initial abstraction or the threshold precipitation depth for runoff to occur (cm) and can be calculated using Equation (33)

S = watershed storage (cm) and is calculated as shown in Equation (34)

$$Ia = 0.2S \quad (33)$$

$$S = \frac{2540}{CN} - 25.4 \quad (34)$$

where

CN =curve number

Based on Antecedent Moisture Class (AMC), CN is modified using either Equation (35) or (36) for drier (AMC I) or wetter condition (AMC II), respectively (Chow et al., 2003).

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \quad (35)$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)} \quad (36)$$

where

$CN(I)$ = curve number for drier condition

$CN(II)$ = curve number for the average of dry and wet condition

$CN(III)$ = curve number for wetter condition

3. The moisture content in biosolids increases the annual average infiltration rate by:

$$\frac{R_{appl} \left(1 - \frac{sd}{100}\right)}{365\rho_{H_2O}} \quad (37)$$

where

R_{appl} = wet biosolids application rate $\left(\frac{Mg}{m^2 year}\right)$

sd = weight percent solids in biosolids

ρ_{H_2O} = density of water $\left(\frac{g}{cm^3}\right)$

4. Biosolids contaminant concentration used in simulation is assumed to be present in the solids portion of biosolids and is repartitioned among the solid, aqueous and gas phases in the till zone.
5. Addition of biosolids to soil does not significantly change the hydraulic properties of soil.
6. Total porosity in the till zone consisting of biosolids and soil mixture is estimated using the relationship for porous media (Freeze and Cherry, 1979).

$$\eta_{till} = 1 - \frac{\rho_{b,till}}{2.65} \quad (38)$$

where

η_{till} = total porosity of till zone

$\rho_{b,till}$ = dry bulk density of the till zone and is calculated as shown in Equation (39)

$$\rho_{b,till} = \rho_{b,soil} \frac{d_{soil}}{z_{till}} + \rho_{b,biosolids} \frac{d_{biosolids}}{z_{till}} \quad (39)$$

where

d_{soil} = depth of soil in till zone and is calculated as shown in Equation (40)

$d_{biosolids}$ = depth of biosolids in till zone and is calculated as shown in Equation (41)

z_{till} = depth of till zone (m)

$$d_{soil} = z_{till} - d_{biosolids} \quad (40)$$

$$d_{biosolids} = \frac{W}{\rho_{b,biosolids}} \quad (41)$$

where

W = wet biosolids loading rate for a single application and is calculated as shown in Equation (42)

$$W = \frac{R_{appl} \frac{sd}{100}}{N_{appl}} \quad (42)$$

where

R_{appl} = wet biosolids application rate $\left(\frac{Mg}{m^2 year} \right)$

sd = weight percent solids in biosolids

N_{appl} = Number of biosolids applications per year

7. Significant build up or degradation of soil surface at the biosolids land application site does not occur with biosolids application or with erosion, respectively. In other words, the depth of the distance from the site surface to any fixed point below does not change with either biosolids addition or with processes such as soil erosion. This may result in contaminant build up in the till zone above contaminant concentration in biosolids for immobile or persistent constituents.
8. The first order loss processes modeled in the till zone include aerobic biodegradation $k_{ae} \left(\frac{1}{d} \right)$ and hydrolysis $k_{hy} \left(\frac{1}{d} \right)$.
9. For an active biosolids site, first order loss rates resulting from wind erosion $k_{wd} \left(\frac{1}{d} \right)$, vehicular activity on the surface of the site and tilling operations are applied to the surface layer of the till zone and are calculated as annual averages. In the case of an inactive biosolids land application site wind erosion is the only first order loss rate process considered.
10. The topmost soil column layer in GSCM serves as the soil compartment for both local watershed and soil column modules and the depth of each of the layers, dz (cm) in the soil column including the surface layer is 0.01 m.

Chemical fate and transport during a storm runoff event at a biosolids land application site is simulated using the soil column module and the local watershed module. The surface layer of GSCM serves as the soil compartment in the combined local watershed and soil column conceptual model (Figure 4). The concentration estimates from GSCM surface layer are called as needed by the local watershed module. It is also assumed that solids and contaminant concentration in the runoff are at instantaneous steady state during each runoff event. It is assumed that hydrolysis, volatilization and biodegradation processes do not occur in the runoff

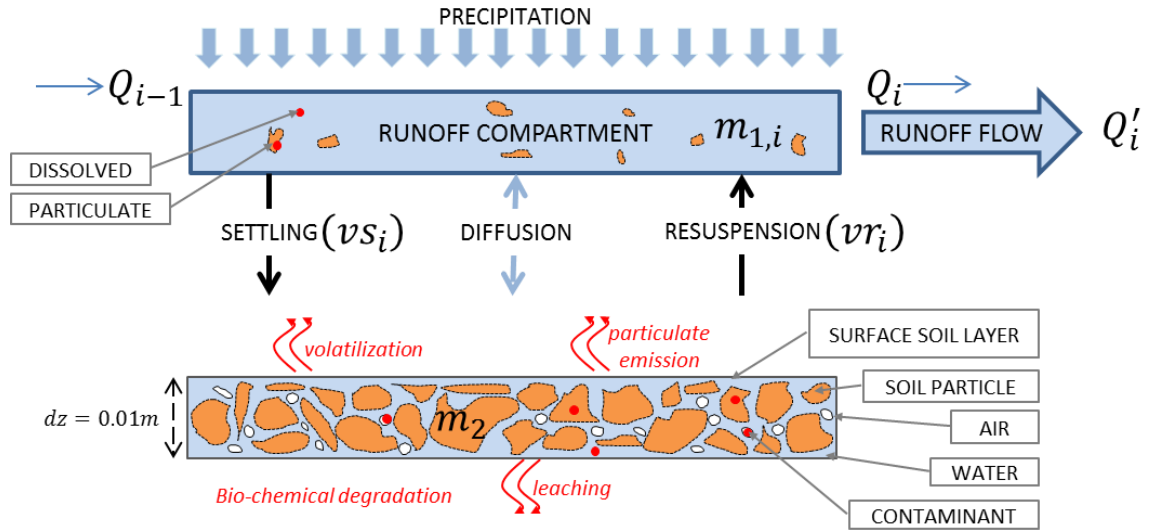


Figure 4. Surface runoff (surficial layer of the soil column). Volatilization from runoff compartment is not simulated as this occurs only for a brief period.

$$0 = Q'_{i-1}m_{1,i-1} - Q'_im_{1,i} - vs_iA_im_{1,i} + vr_iA_im_2 \quad (43)$$

compartment. The assumption is justified as the percentage of time during which runoff occurs is sufficiently short. The first term in Equation (43) is the soil flux from the subarea up slope of the subarea i , the second term is the soil flux leaving subarea i , the third and fourth terms are the internal sink due to settling and internal source due to resuspension, respectively.

where

Q'_{i-1} = runoff from subarea $i - 1$

$m_{1,i-1}$ = solids concentration in runoff from subarea $i - 1$

Q'_i = total runoff volume:water and solids leaving subarea

$m_{1,i}$ = solids concentration in runoff from subarea i

vs_i = settling velocity

A_i = surface area of subarea i

vr_i = resuspension velocity

m_2 = solids concentration in top layer of the soil column

As transport among watershed subareas are not considered in GSCM, the combined module simulates the vertical transport into the runoff compartment. In the surface layer of the soil column, settling, resuspension and burial or erosion is simulated. The steady-state mass balance equation to simulate these three processes is shown in Equation (44). The first term in Equation (44) models settling, the second term models resuspension and depending on the sign of the third term either burial occurs or erosion is modeled.

$$0 = v_{s_i} m_{1,i} A_i - v r_i m_{2,i} A_i - v b_i m_{2,i} A_i \quad (44)$$

Equation (44) has three parameters; namely, v_{s_i} , $v r_i$ and, $v b_i$ and two concentrations: m_1 and m_2 . m_2 is assumed to be equal to bulk density of soil (soil and biosolids mixture). The value of m_1 is calculated as given in Equation (45).

$$m_{1,i} = \frac{CSL_i}{Q'_i} \quad (45)$$

where

CSL_i = cumulative soil load leaving subarea i

CSL_i is calculated using Modified Universal Soil Loss Equation (MUSLE) approach used in the Soil Erosion Module. Settling velocity (v_{s_i}) is assigned based on a distribution given in US EPA, 1999b. $v b_i$ and $v r_i$ are calculated as shown in Equation (46) and (47), respectively.

$$v b_i = \frac{CSL_{i-1} - CSL_i}{A_i m_2} \quad (46)$$

$$v r_i = v_{s_i} \frac{m_{1,i}}{m_2} - v b_i \quad (47)$$

The mass balance of the chemical constituent in the runoff compartment is given in Equation (48).

$$0 = Q'_{i-1}c_{1,i-1} - Q'_i c_{1,i} - v_{s_i} A_i Fp_{1,i} c_{1,i} + v_{r_i} A_i Fp_{2,i} Er_i c_{2,i} + v_{d_i} A_i \left(\frac{Fd_{2,i}}{\Phi_2} c_{2,i} - \frac{Fd_{1,i}}{\Phi_{1,i}} c_{1,i} \right) \quad (48)$$

where

$c_{1,i}$ = total contaminant concentration (particulate and dissolved) in runoff from subarea i

$Fp_{1,i}$ = fraction particulate in runoff

$Fp_{1,i}$ is calculated based on Thomann and Mueller (Thomann and Mueller, 1987) as shown in Equation (49).

$$Fp_{1,i} = \frac{\frac{k_d}{\Phi_2} m_2}{1 + \frac{k_d}{\Phi_2} m_2} \quad (49)$$

where

k_d = chemical specific partition coefficient

Er_i = enrichment ratio

Er_i accounts for preferential erosion of finer particles and is calculated as shown in Equation (50).

$$Er_i = \frac{a}{\left(\frac{CSL_i}{WSA_i} \right)^{0.2}} \quad (50)$$

where

$$a = 7.39 \text{ for } \frac{CSL_i}{WSA_i} \text{ in } \frac{kg}{ha}$$

WSA_i = local watershed area from drainage divide upstream and the area of the subarea i

$c_{2,i}$ = total contaminant concentration in soil

vd_i = diffusive exchange velocity

$Fd_{1,i}$ = fraction dissolved in runoff. It is calculated as shown in Equation (51).

vd_i it is calculated as shown in Equation (54) (Thomann and Mueller, 1987).

$$(1 - Fp_{1,i}) \quad (51)$$

Φ_2 = soil porosity. It is calculated as shown in Equation (52).

$$\Phi_2 = 1 - \frac{m_2}{\rho} \quad (52)$$

where

$\Phi_2 = \eta$ in *GSCM*

$\Phi_{1,i}$ = is the porosity of runoff. It is calculated as shown in Equation (53).

$$\Phi_{1,i} = 1 - \frac{m_{1,i}}{\rho} \quad (53)$$

where

ρ = density of the suspended particles

$$vd_i = \frac{Dw}{\Phi_2 Lc} \quad (54)$$

where

D_w = water diffusivity

L_c = assumed to be the depth of runoff and is defined as the characteristic mixing length over which the chemical concentration gradient exists.

L_c is calculated as shown in Equation (55).

$$L_c = \frac{Q'_i}{A_i} \quad (55)$$

The governing equation for GSCM for the surface layer can now be written as shown in Equation (56).

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - \sum k_j C_{2,i} + ss_i \quad (56)$$

where

k_j = first order loss process but does not include runoff or erosion process

ss_i = net effect of runoff or erosion process on $C_{2,i}$

ss_i represents either a source or a sink. It is calculated as shown in Equation (57).

$$ss_i = a_i C_{1,i} - b_i C_{2,i} - k_{bu,i} C_{2,i} \quad (57)$$

Where a_i , b_i and $k_{bu,i}$ are defined in Equations (58), (59) and (60), respectively.

$$a_i = \frac{vs_i F p_{1,i} + v d_i \frac{F d_{1,i}}{\Phi_{1,i}}}{dz} \quad (58)$$

$$b_i = \frac{vr_i Fp_{2,i} Er_i + vd_i \frac{Fd_{2,i}}{\Phi_2}}{dz} \quad (59)$$

$$k_{bu,i} = \frac{vb_i Fd_{2,i}}{dz} \quad (60)$$

Equation (57) can be rewritten as shown in Equation (61).

$$\begin{aligned} \frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - \sum k_j C_{2,i} + a_i C_{1,i} - b_i C_{2,i} \\ - k_{bu,i} C_{2,i} \end{aligned} \quad (61)$$

As $C_{2,i}$ is a function of $C_{1,i}$; $C_{1,i}$ can be expressed in terms of $C_{2,i}$ as shown in Equation (62).

$$C_{1,i} = \frac{Q'_{i-1} C_{1,i-1}}{d_{2,i}} + \frac{d_{1,i}}{d_{2,i}} C_{2,i} \quad (62)$$

Where $d_{1,i}$ and $d_{2,i}$ can be expressed as shown in Equations (63) and (64), respectively.

$$d_{1,i} = vr_i A_i Fp_{2,i} Er_i + vd_i A_i \frac{Fd_{2,i}}{\Phi_2} \quad (63)$$

$$d_{2,i} = Q'_i + vs_i A_i Fp_{1,i} + vd_i A_i \frac{Fd_{1,i}}{\Phi_{1,i}} \quad (64)$$

Now, Equation (61) can be expressed using $d_{1,i}$ and $d_{2,i}$ as shown in Equation (65).

$$\begin{aligned} \frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} \\ - \left(\sum k_j + b_i + k_{bu,i} - \frac{a_i d_{1,i}}{d_{2,i}} \right) C_{2,i} \\ + \frac{a_i Q'_{i-1} C_{1,i-1}}{d_{2,i}} \end{aligned} \quad (65)$$

$C_{2,i}$ is determined and then substituted in Equation (66) to obtain the value of $C_{1,i}$.

Equation (65) can be further simplified to implement the simultaneous solution and is given in Equation (66).

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - k'_i C_{2,i} + ld_{i-1} \quad (66)$$

where

k'_i = lumped first order loss rate and is expressed as shown in Equation (67).

ld_{i-1} =runoff load from upslope subareas $\left(\frac{g}{m^3} \frac{d}{d}\right)$ and is calculated as shown in Equation (69).

$$k'_i = \sum k_j + k_{ev,i} + k_{bu,i} \quad (67)$$

where

$k_{ev,i}$ = storm event first order loss rate and is expressed as shown in Equation (68).

$$k_{ev,i} = b_i - a_i \frac{d_{1,i}}{d_{2,i}} \quad (68)$$

$$ld_{i-1} = \frac{a_i}{d_{2,i}} Q'_{i-1} C_{1,i-1} \quad (69)$$

The first two components representing diffusion and convection remain the same for the surface layer, but the third component as shown in Equation (56) is solved as shown in Equation (70) and the analytical solution as shown in Equation (71).

$$\frac{\partial C_{2,i}}{\partial t} = k' C_{2,i} + ld_{i-1} \quad (70)$$

$$C_{2,i} = \begin{cases} C_{2,i}^0 \exp(-k'_i t) + ld_{i-1} \left[\frac{1 - \exp(-k'_i t)}{k'_i} \right] & k'_i > 0 \\ C_{2,i}^0 + ld_{i-1} t & k'_i = 0 \end{cases} \quad (71)$$

where

$$C_{2,i} = C_{2,i}^0 \text{ at } t = 0$$

The mass added to the surface soil layer of the soil column from settling from runoff water is calculated as shown in Equation (72). The change in mass in the soil column is then calculated as shown in Equation (73).

$$M_{add,i} = l d_{i-1} t dz \quad (72)$$

$$\Delta M_i = M_{add,i} - M_{loss,i} \quad (73)$$

where

$M_{loss,i}$ = total mass lost in subarea i in time from zero to t and is calculated as shown in Equation (74).

$$M_{loss,i} = \left[C_{2,i}^0 (1 - \exp(-k'_i t)) + l d_{i-1} \left(\frac{k'_i t + \exp(-k'_i t) - 1}{k'_i} \right) \right] dz \quad (74)$$

The first order losses that are accounted for in the model individually can be calculated using the Equation (75).

$$M_{j,i} = M_{loss,i} \frac{k_j}{k'_i} \quad (75)$$

where

j = processes for (1) hydrolysis, (2) aerobic degradation, (3) loss due to wind and mechanical activity, (4) runoff and erosion events and (5) burial or erosion.

The average chemical contaminant concentration in runoff water and in the soil compartment is calculated as shown in Equation (76) and (77), respectively.

$$\bar{C}_{1,i} = \frac{Q'_{i-1} \bar{C}_{1,i-1}}{d_{2,i}} + \frac{d_{1,i}}{d_{2,i}} \bar{C}_{2,i} \quad (76)$$

$$\bar{C}_{2,i} = \frac{C_{2,i}^0 + C_{2,i}}{2} \quad (77)$$

CHAPTER 3

METHODOLOGY

3.1. Modified 3MRA Model

3MRA model version 1.0 (base model) was modified to better characterize a biosolids land application practice. The source code for the base model was obtained from US EPA and modifications were made to incorporate additional processes to achieve site specificity. Two models were developed, one targeting POTW managers for screening level risk assessment and other that accounts for a greater level of site specificity. The screening level model only estimates hazard from ingesting groundwater Figure 5. The user's manual is provided in the Appendix B.

The base model did not account for annual variations in agricultural practices such as biosolids application rates, annual variability in crop type as well as changes in biosolids characteristics between years. These changes were made as these parameters are sensitive to the risk or hazard quotient estimate and are illustrated in the Groundwater pathway section (section 4.5) by varying each of these parameters using one parameter at a time sensitivity analysis. Broadly, changes made to the base model includes: accounting for background soil concentration, incorporation of annually variable parameters that describes a typical biosolids land application practice as well as annually variable parameters that describes biosolids characteristics. A complete description of the changes made are provided in the following paragraphs in greater detail and the schematic of the modified GSCM is shown in Figure 6 and Figure 7.

Biosolids and Groundwater Risk Screening Tool

File

Site ID	Site Name	Site Specific Inputs
0136703	Tucumcari, NM	Waste Properties
0223504	Orville, OH	Selected pollutant concentration (mg/kg)
0312301	Borger, TX	Waste application rate (dry tons/ acre-year)
0332104	Dayton, VA	Percent solids in waste (mass %)
0435510	Havana, IL	Fraction organic carbon (Biosolids, mass fraction)
0530901	Huron, OH	Bulk density, Biosolids (lb/cubic yard)
0625501	Dayton, TX	Average biosolids pH (pH units)
0631701	Deer Park, TX	Biosolids Management Properties
0720803	Plantation, FL	Tillage Depth (ft)
0831904	Clyattville, GA	Operating Life (yr)
1010805	Van Buren, AR	No. of cultivations per application
1031503	Flowery Branch, GA	
1032802	Salina, KS	
1033202	Plainwell, MI	
1033602	Pittsboro, NC	
1034005	Rheims, NY	
1034210	Richmond, UT	
1035508	Walla Walla East, WA	
1131802	Roseville, CA	
1133902	Hanibal, MO	
1134405	Watts Mills, SC	
1231101	Wando, SC	
1231705	Memphis, TN	
1333001	Florence, SC	
1522504	Red Lion, DE	
1621808	Senoia, GA	
1631701	Washington, NC	
1632106	Tortugas, NM	

Site Characterisation

Depth to water table (ft)

Location of nearest receptor X (m) Y (m)

Site Area (acres)

Groundwater flow direction in degrees from north

Indicator for degree of fracturing of saturated porous media

Average vadose Zone pH (pH units)

Saturated hydraulic conductivity (subsoil, cm/hr)

Fraction organic carbon (soil, mass fraction)

Regulated Pollutants

Arsenic
Cadmium
Divalent Mercury
Methyl Mercury
Elemental Mercury
Ni+2
Lead

Messages

Start

Calculate the Agronomic Biosolids Application Rate.

Figure 5. User interface for Biosolids and Groundwater Risk Characterization Tool (BGRST).

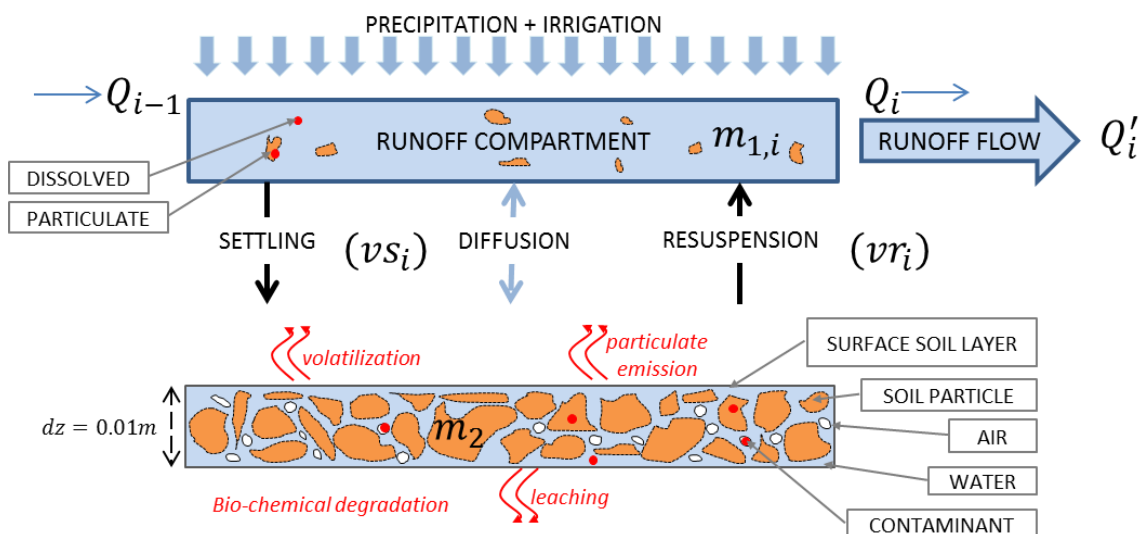


Figure 6. Schematic of modified GSCM (surface soil-runoff component).

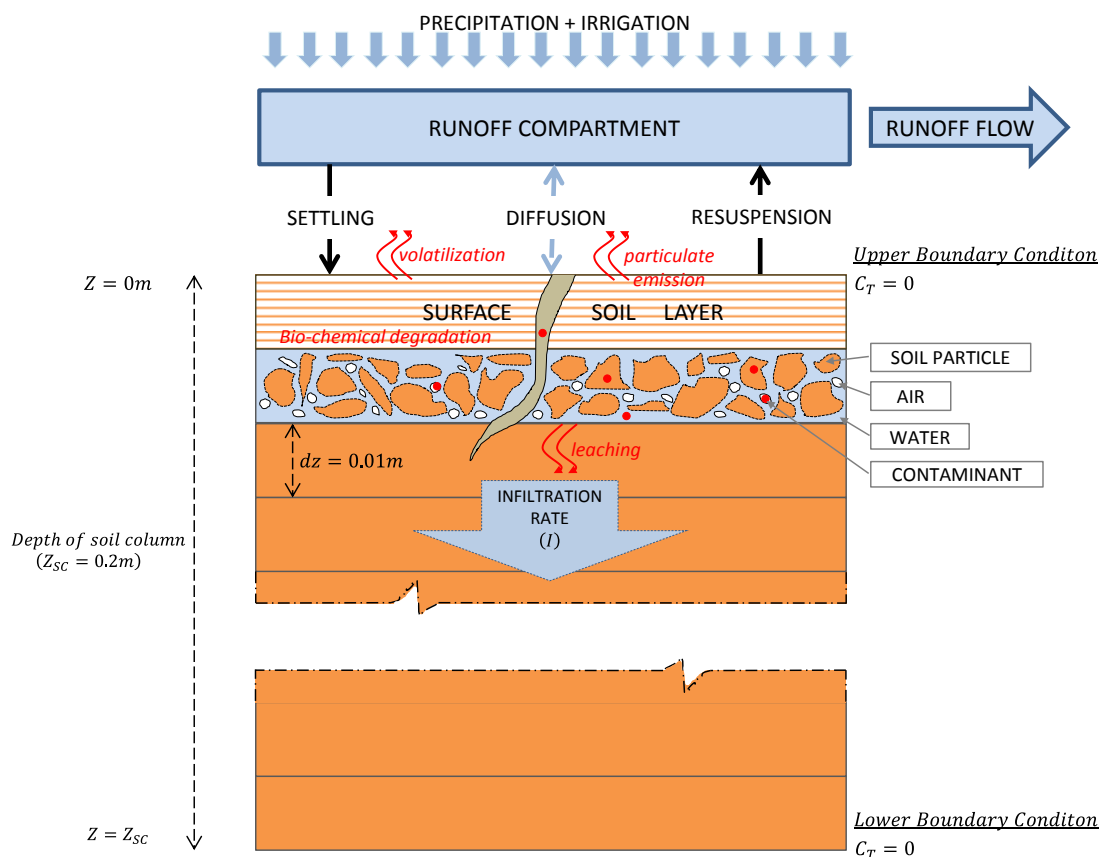


Figure 7. Modified GSCM model with plant uptake and irrigation.

3.1.1. Background Concentration

Prior to biosolids application for the year 1994 the measured concentration of As and Cd in the till zone was 6.34 mg/kg DW basis and 4.0 mg/kg DW basis, respectively (King County, 1995). A single data point was reported for the site for both As and Cd. Organic constituents were not reported for the site as the facility is not mandated by Part 503 to sample B(a)P or DEHP concentrations in the soil. The base model assumes a biosolids application site is chemical contaminant free at the start of simulation. This shortcoming of the model will not allow for proper calibration or validation of the model. Therefore, the contaminant concentration in the soil at the beginning year of the simulation is added to initialize the soil contaminant concentration. Additionally, such approaches have been recommended earlier in the context of

sewage sludge first order metal loss studies simulating contaminant mass lost from the zone of biosolids incorporation (Steenhuis et al., 1999). Background contaminant concentration is therefore defined here as the concentration in the soil (till zone of the biosolids land application site) at the beginning of the simulation. For the purposes of this effort no distinction is made for the origin of this initial concentration which could be, for example, due to the parent material or due to contaminant introductions from agricultural management practices that have occurred at the site prior to the start of the simulation year. The change was made to the model source code to update the ConcZ1[] array (g/m^3) within the year loop in the LAUModel() function of LAU class in the LAU.cpp file. Stated differently, ConcZ1 [] array is initialized with an initialized concentration of the contaminant being simulated to represent the background concentration.

3.1.2. Annually Variable Water Input

The base model does not account for increased leaching as result of introducing irrigation water or from changes in the percent solids of the applied biosolids for a particular year. It only accounts of an initialized state of percent solids and applies the resulting water from the applied biosolids to all years when a biosolids land application occurs. Additionally, this occurs only till the CutOffYr specified by the modeler to represent the number of years the practice is occurring. However, consecutive applications did not occur at the site, meaning such a case cannot be modeled within the base model construct. Hence, to account for no application and the resulting zero additional water contribution from the biosolids, annually variable percent solids rate was specified to coincide with the application. Additionally, Yakima Valley is arid and agriculture primarily relies on irrigation water as annual precipitation is not sufficient to meet the water requirements of the crops (Coulter, 1951; King County, 1999; Fisher and Healy, 2008). Thus, by not including irrigation water component the effect of leaching will be

unaccounted by the model. Therefore, to account for these two additional water inputs, the source code was modified to include the water available for infiltration as that contributed by water in biosolids (for only those years when biosolids are applied) and that contributed by irrigation water (applied for all years there is cultivation). Specifically, the source code was modified by adding irrigation water that varies annually based on crop planted for a particular year to the Infil variable in the LAUModel function of the LAU class (LAU.cpp file). Based on the percent solids for any year new water input was calculated and added to the irrigation water component. In other words, the water contributed by biosolids will depend on both the application rate and percent solids, both of which vary with each of the years that are simulated. Furthermore, both the irrigation water and biosolids water components are updated only during the years when there is crop cultivation and biosolids land application.

3.1.3. Annually Variable Plant Uptake

The base model simulates plant uptake of chemical contaminants; however, not from the actual application site itself (US EPA, 1999m). Hence, the source code was modified to account for plant uptake at the site, thus allowing for contaminant loss through this pathway. A linearized uptake coefficient specific to a particular crop reduces the contaminant available in the soil column. The current implementation reduces the simulated contaminant in the till zone for each year when there is cultivation. The plant uptake function is implemented within the DoApplication function of the Land class (Land.cpp file) contained in the 3MRA source code.

3.1.4. Variable Biosolids Application Rate and Contaminant Concentration

The 3MRA model considers one application rate for the entire simulation (US EPA, 1999m). However, actual biosolids land application practice involves changes in the application rates for different years as it is a function of crop being cultivated and the amount of N

remaining from previous applications (King County, 1996; King County, 1997; King County, 1998; King County, 1999). Thus, a realistic application scenario will have to involve annual variability in biosolids application rate. The variable application rate is implemented within the DoApplication function of the Land class (Land.cpp file). As the contaminant concentration also changes between years (King County, 1996; King County, 1997; King County, 1998; King County, 1999), the model was also modified to reflect this change. The base model only accounts for an initialized state of contaminant concentration for the entire simulation (US EPA, 1999m). This change was also implemented within the DoApplication function of the Land class (Land.cpp file).

3.1.5. Variable PM30 Rates from Vehicular Activity

The particulate emissions function that computes the PM30 (i.e., particles less than 30 μm in diameter) emissions resulting from vehicular activity was modified to account for changes in application rate that leads to changes in the number of vehicles that will have to be used to apply biosolids at the site. The particle size distribution is specified similar to the model implementation of HWIR99 (US EPA, 1999a). Thus, the “nv” variable was updated for each year when there is a different application rate from the previous year to calculate the number of vehicles. This change was made to the DoParticulateEmissions function in the Land class (Land.cpp file). In addition to capturing the effects of variable application rates on vehicular activity, change was made to account for the continuation of agricultural operations beyond the termination of biosolids application. It is specified by the CutOffYr variable which was updated for the entire simulation period rather than just the number of years of application to reflect continued use of land for cultivation.

3.2. Survey and Study Area Selection

The study area selection process was based on repeat surveys and evaluation of annual reports from POTWs that were engaged in biosolids land application as one of their disposal options. The survey was performed nationally from a random group of facilities that were geographically diverse. Three biosolids land application surveys were conducted that encompassed ten states across different geographic and climatic regions in the US. The survey was designed to gather information about the data that is being collected by the facilities in order to identify POTWs that could help with the data needs of the 3MRA model. Part 503 mandates monitoring and recordkeeping of nine constituents only (US EPA, 1993) and all facilities surveyed comply with those requirements. On the other hand, only two facilities measured or monitored other chemical constituents present in biosolids. None of the facilities surveyed monitored organic constituents in the till zone, groundwater or elsewhere. The survey also revealed key information with regards to the non-existence of any regulatory requirements in terms of monitoring groundwater at land application sites irrespective of groundwater use (e.g., potable vs. non-potable use). A brief summary of the information pertaining to the study gleaned from the survey is presented in Table 6.

The King County, Washington (WA) biosolids program was identified as the most suitable program in terms of satisfying the data requirements of this modeling effort from the facilities surveyed. Hence, Natural Selections Farm (NSF) biosolids land sites located within Yakima County in WA was selected. From all biosolids land application sites available, one site was selected as it satisfied the data requirements needed to characterize the facility as well as the data needed for calibration and validation of the model. In addition to the data requirements, this specific site was selected as it contained a groundwater well that could

Table 6. Summary of the suitability of a POTW for the study

States Surveyed	AR	CA	GA	KS	MI	NV	PA	UT	VA	WA
Number of facilities surveyed	1	1	1	1	2	1	1	2	1	3
Depth to groundwater monitoring	No	N/A	N/A	No	N/A	Yes	Yes	No	Yes	Yes
Use of groundwater	potable	N/A	N/A	DK	N/A	DK	non-potable	non-potable	DK	potable
Monitoring wells up or down gradient	N/A	N/A	Yes	No	N/A	N/A	No	DK	Yes	Yes
Organic constituent Monitoring Program	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes
Surface water monitoring program	N/A	N/A	Yes	No	N/A	N/A	No	DK	Yes	Yes

DK: Don't Know

N/A: Not Applicable

potentially have least interference from other application sites. The site selection criteria are listed below:

1. Presence of a groundwater monitoring program:
 - a. Collection of depth to groundwater data.
 - b. Groundwater contaminant monitoring data (at least regulated contaminants).
 - c. Use of groundwater for drinking water purposes (to assess actual risk from drinking contaminated water).
2. Monitoring of organic constituents in biosolids
3. Surface water monitoring program:
 - a. TSS monitoring.
 - b. Chemical constituent monitoring (at least regulated pollutants).
4. A biosolids land application program that contained repeat applications and multiple measurements for soil and groundwater chemical contaminant data.

3.3. Study Area

The biosolids land application site considered in this study is located in Yakima County in Washington State. The site received biosolids from two waste water reclamation facilities generating biosolids in King County as well as biosolids from the City of Sunnyside located in Yakima County WA (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). The Yakima River flows downstream of the land application site in the southeasterly direction and is a tributary to the Columbia River. The entire Yakima River basin is reported as one of the most intensely irrigated agricultural regions in the United States with return flows as high as 90% during the irrigation season. NSF oversees the biosolids land application program as well as monitors soil and groundwater for all pollutants regulated under Part 503. King County gathers data on trace organics for the biosolids (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). Thus, making the site ideal for this modeling effort both from model population to calibration and validation of the developed model. Figure 8 shows the study area. Average annual precipitation for the area is 20 cm (Opitz-Stapleton et al., 2007) with agriculture primarily dependent on irrigation (Fisher and Healy, 2008; Vano et al., 2010). The depth to groundwater in the wells in the region ranged from approximately 10 feet to 150 feet (US EPA, 2013). The concentration of total As and Cd at the monitoring well has remained below the MCL for the years that data exists (Figure 9).

3.4. Data Compilation and Processing

This section documents the data collection effort to support a successful execution of modified 3MRA model with focus for site specificity. It documents the data compilation and processing effort and includes data collection, data sources, methodology, data gaps and

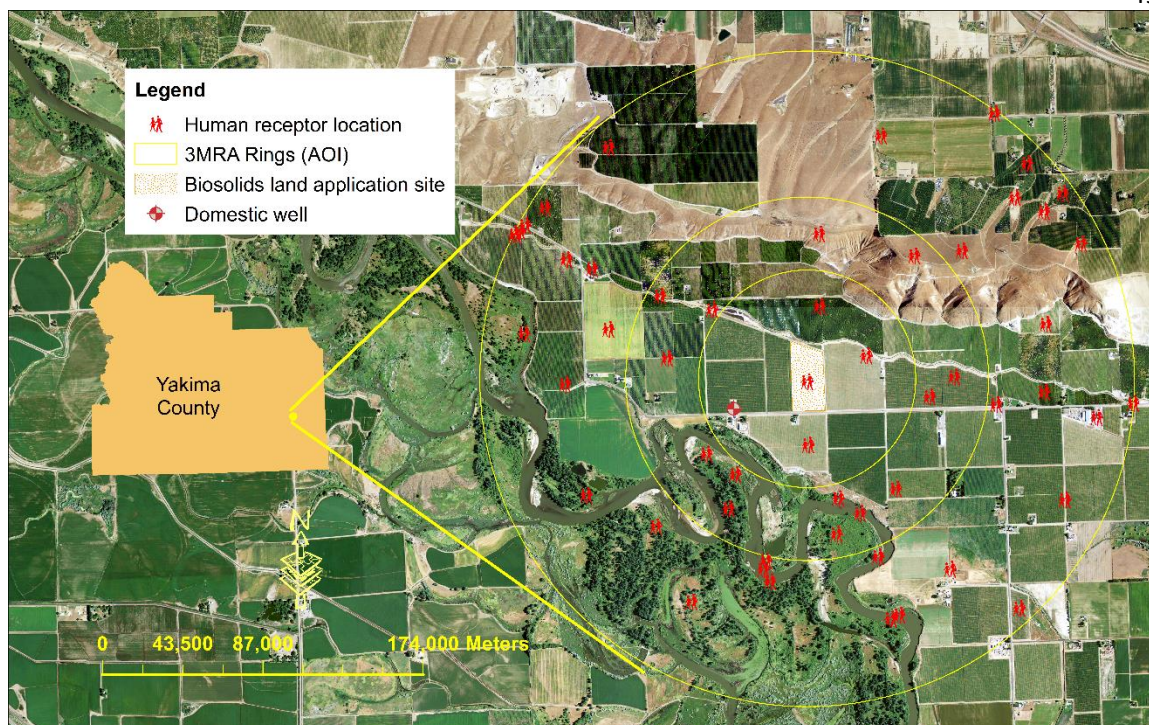


Figure 8. Study area.

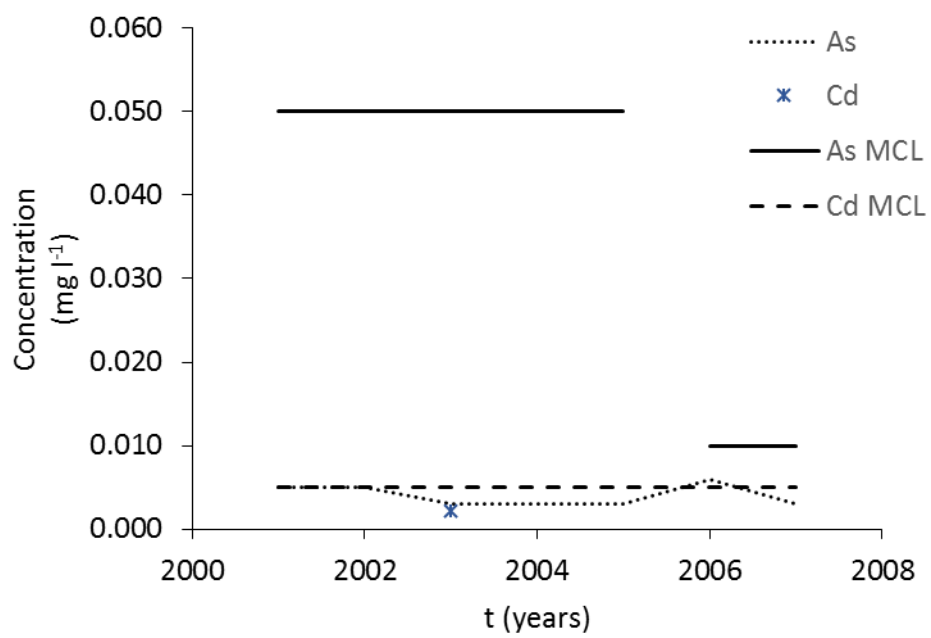


Figure 9. Variation of measured total As and total Cd in the groundwater monitoring well.

accuracy of the data set. Although, the data collection effort is centered on site specificity, data was gathered from national and regional studies when site specific data was not available. Nine modules from 3MRA model applicable to this study are: one source module (LAU), five fate and transport modules (air, watershed, surface water, vadose zone and aquifer), one exposure module (human exposure), one risk module (human risk) and the exit level processor. This section is subdivided into nine subsections, namely; air, LAU, saturated zone, site layout, biosolids characteristics, soil, vadose zone, chemical properties and meteorological data and are described in detail.

Although 3MRA uses Microsoft Access database (a relational database management system), it is not implemented as a relational database. Three different databases are used by 3MRA, namely, site specific, regional and national (US EPA, 1999d). Site specific data were entered in all three databases of 3MRA when available. In other words, data which were contained in national or regional databases were converted to site specific data when available at site level, thus maintaining the parent data structure and hierarchy of the databases. The distribution types for data were also changed to account for uncertainty, variability and for management practices that are specific to biosolids land application practice. Specific details and the reasoning behind conversion of parent data distribution to a different distribution type are covered in the appropriate sections describing the data processing effort.

3.4.1. Air

Six parameters in the site level database represent the air data group and are listed in Table 7 along with their description. Anemometer height (AnemHght - surface station) is used by the air module of 3MRA which is the Industrial Source Complex-Short Term (ISCST3) Version 3.0 (US EPA, 1999a). For the case of biosolids LAU, the source height (SHght) is equal to zero. The

Table 7. Parameters in air data group

3MRA Variable Name	Description	Units	Distribution Type
AirData	Upper air meteorological station number	NA	constant
AnemHght	Anemometer height	m	constant
RuralStr	Rural or Urban area	NA	constant
SHight	Source height	m	constant
StartYr	Starting year of meteorological file	NA	constant
SurfData	Surface station number	NA	constant

NA – Not applicable

data source for all parameters in this data group were gathered from the National Climatic Data Center (NCDC) website site description files. The surface station which contained all the required meteorological data that satisfies the data quality objectives is in Yakima, WA (surface station number: 24243) and the closest upper air meteorological station for the study area is located in Spokane, WA (Mixing height station number: 24157) (US EPA, 1999f). For the purpose of this modeling effort, the study area is considered as rural and was determined based on land use (US EPA, 1995; US EPA, 1999I). The start year for the calibration model is 1994 and for the validation model it is 1997.

3.4.2. Land Application Unit (LAU)

The LAU data in the site database are listed in Table 8 along with a brief description about how the data was processed along with their sources. The biosolids land application site is contained within one watershed sub-basin and divides it into two areas as illustrated in Figure 10. The subarea one is the application site and the subarea two is the downstream buffer region and slopes towards the southwest direction. LAU data contained within the site database is defined for both of these sub-regions; however, not shown in Table 8. On the other hand, the appendix contains the entire dataset.

3.4.3. Saturated Zone

The variables that are required to execute the saturated zone module are listed in Table 9. Limited availability of well specific data describing the needed parameters were the primary reason of uniform distribution assignment for distribution type.

3.4.4. Site Layout

The spatial relationships of all components such as the biosolids land application site, watershed subbasins, waterbody networks and others are grouped and described under the site layout data group of the site database. The relationships between spatial components such as

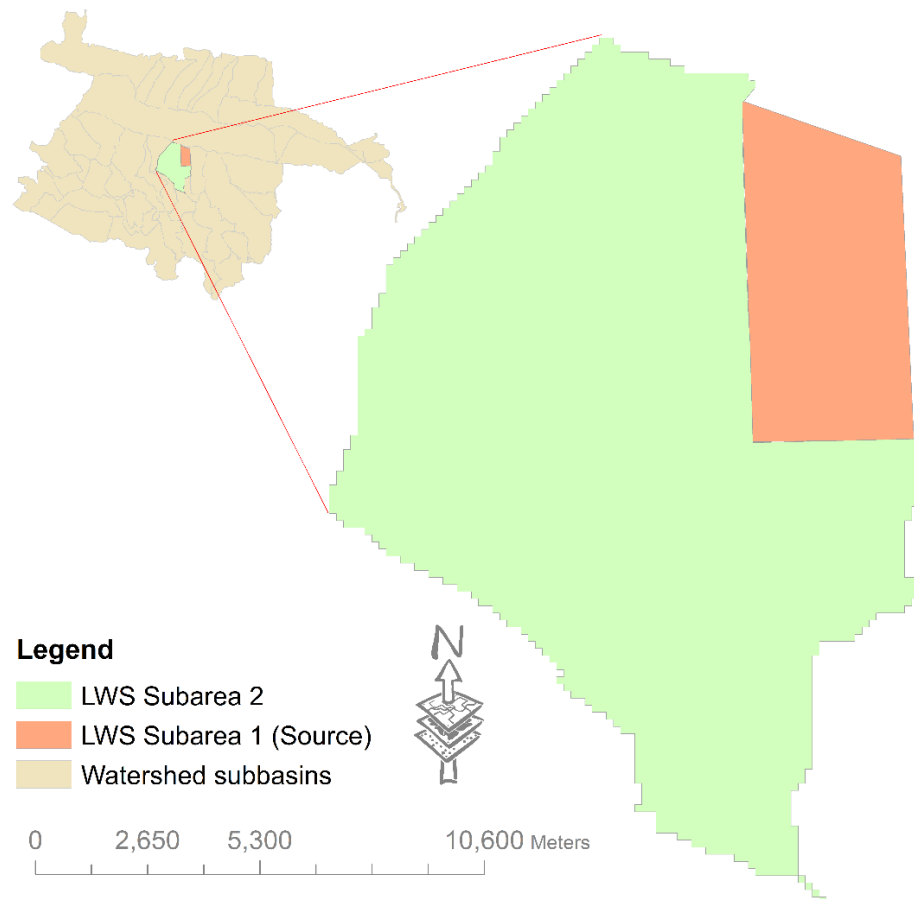


Figure 10. Disaggregation of the watershed subbasin that contains the site. Subarea 1 represents the biosolids land application site and subarea 2 represents the buffer region.

Table 8. Land application unit data in site database

Description	Name	Units	Data source/ Processing	Calculation	Value and distribution type
USLE cover factor for the site	C	unitless	(Wanielista and Yousef, 1993; US EPA, 1999e; NRCS, 2014)	NA	0.08
SCS curve number for LWS subareas	CN	unitless	(US EPA, 1999e; NRCS, 2014) (for hydrologic soil group: B)	NA	74, constant
SCS curve number for site	CNwmu	unitless	(US EPA, 1999e; NRCS, 2014) (for hydrologic soil group: B)	NA	74, constant
Depth of root zone	DRZ	cm	(US EPA, 1999h)	Look up table 7-10	125, constant
Number of cultivations per application	fcult	unitless	(US EPA, 1999e)	$<0.01 \frac{Mg}{m^2}$	1, Constant
Frequency of surface disturbance per month for active site	fd	1/mo	(US EPA, 1999e)	$\frac{N_{appl} \times f_{cult}}{12}$	0.083333, Constant
Fraction organic carbon	focS	mass percent	(Albanese and Allen-King, 1997)	Look up table	0.057 - 0.094, uniform distribution
Soil hydrologic group	HydroGroup	Unitless	(NRCS, 2014)	NA	
USLE erodibility factor	K		(NRCS, 2014)	NA	0.64
Saturated hydraulic conductivity	Ksat	cm/hr	(NRCS, 2014)	NA	1.44 to 5.04, uniform
USLE erodibility factor for site	Kwmu		(NRCS, 2014)	NA	0.64
Mean annual vehicles per day	nv	1/d	(US EPA, 1999e)	$\frac{area(m^2) \times R_{appl} \left(\frac{Mg}{m^2 - yr} \right)}{payload(Mg) \times 365.25(d/yr)}$	0.028441 (yr = 1994), 0.020863 (yr = 1995)
Mean wheels per vehicle	nw	unitless	(Albanese and Allen-King, 1997)	NA	8-10, Uniform distribution

Description	Name	Units	Data source/ Processing	Calculation	Value and distribution type
USLE erosion control factor for site	P	unitless	(US EPA, 1999e)	NA	0.5, for cropland
Wet biosolids application rate	Rappl	Mg/m ² -yr	(King County, 1995)	$\frac{\text{dry tons}}{\text{acre}} * 100 \left(\frac{0.907 \text{ Mg}}{4046.86 \text{ m}^2} \right)$	0.001481 for 1994, Constant
Soil moisture coefficient b (surface soil)	SMb	Unitless	(Clapp and Hornberger, 1978)	NA	5.3, for soil texture: silt loam
Field capacity	SMFC	volume %	(NRCS, 2014)	NA	20.1 to 22.4, Uniform
Wilting Point	SMWP	volume %	(NRCS, 2014)	NA	5.3 to 6.8, Uniform
Silt content (soil; top 20 cm)	Ss	mass percent	(NRCS, 2014)	NA	65.7 to 67.7, Uniform
Slope (local watershed)	Theta	degrees	(USGS, 2013a; USGS, 2013b)/ derived data	degrees (atan (2.54/100))	1.403, Constant
Mean vehicle weight	vw	Mg	(US EPA, 1999e)	$vw = \frac{\text{payload}}{2} + w_{\text{empty}}$	22.5, Constant
Saturated water content	WCS	volume fraction	(US EPA, 1999h)	NA	0.43 for soil type: SICL
Flow length	X	m	(USGS, 2013a; USGS, 2013b)/ derived data	NA	1231
Depth of tilling	zZ1WMU	m	(US EPA, 1999e)	NA	0.2, Constant

Table 9. Saturated zone module data

3MRA Variable name	Value	Distribution type	Units	Source/ Processing
AquFractureID	0	Constant	Unitless	(Vaccaro et al., 2009), Not fractured
AquRandHeteroNorm	0	Constant	Unitless	(US EPA, 1999n)
AquDir	180 - 230	Uniform	degrees	(Vaccaro et al., 2009)/ Based on topography
AquTemp	7.3 – 13.3	Uniform	°C	(US EPA, 2013)
AquPh	5.65 – 7.81	Uniform	pH units	(US EPA, 2013)

soils and watershed subbasins are transformed from spatial data (shape files or raster's) to textual data (text files). The specification of “system geometry and connectedness” is essential for site characterization and this data group represented a major challenge in its population. For example, the reach length is a function of number of reaches within a waterbody network, which in turn depends on the number of the waterbody networks. The transformation of spatial data and associated relationships to textual data in 3MRA friendly format was accomplished both manually and through automation and is described in detail in this section. The spatial layout data group represents the largest data group in terms of number of data points required to populate the 3MRA site database. Ninety percent of all data for this modeled site is represented by the site layout data group within the site level data specification.

Stream order (WBNRchOrder) assignment for the reaches was based on Strahler method (Strahler, 1957). Uncorrected WBNRchOrder dataset for the site is shown in Figure 11. The coordinates of each stream reach is represented by WBNRchLocX and WBNRchLocY variables and were generated for all reaches in the three waterbody networks (Figure 12). The index of the reach that impacts a downstream reach is specified in the parameter WBNRchRchIndex (US EPA, 1999g). The indices of the reaches are shown in Figure 13.

To capture the potential risk or hazard from any exposure pathway or a combination of pathways, human receptor data is characterized within the AOI. Human receptor data required

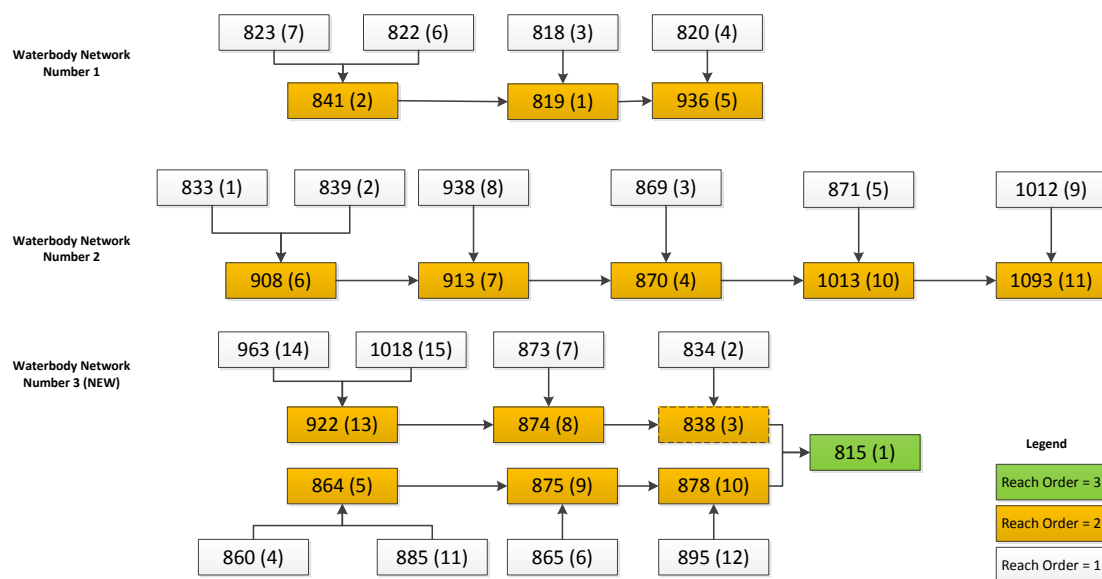


Figure 11. Uncorrected (resulting from DEM artifacts) reach orders for the waterbody network within the AOI.

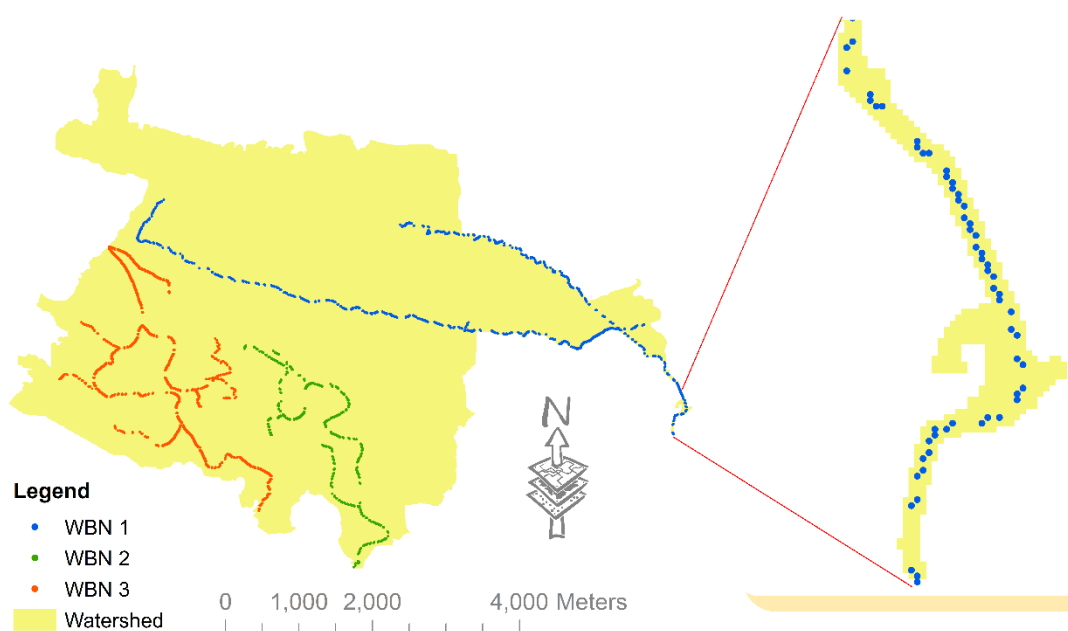


Figure 12. WBN X and Y locations.

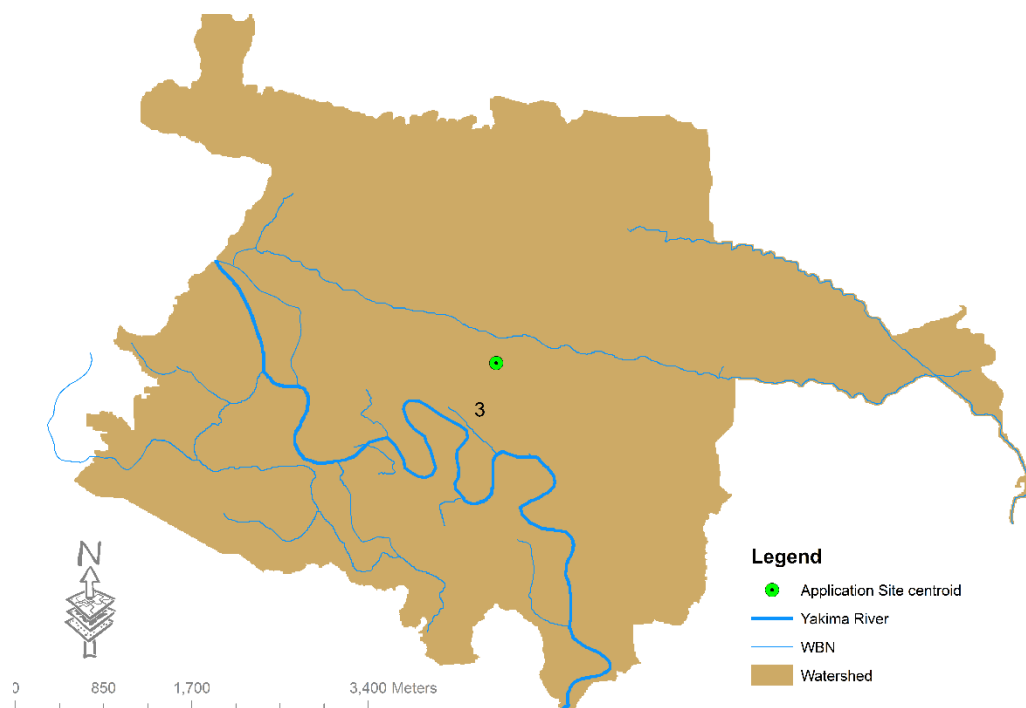


Figure 13. WBNRchRchIndex – Index of waterbody network reaches.

for assessing the risk or hazard includes number of receptors, their location and age (US EPA, 1999j). The census block data was used to populate these parameters as the census block is smallest spatial unit (highest resolution) distributed by the US Census Bureau (US Census Bureau, 2003) and resulted in 526 individuals within the AOI. All human receptors were categorized as residents, resulting in exposure (pathways) from inhalation of ambient air, inhalation of shower air, ingestion of groundwater and ingestion of soil. The resident receptor type were further divided into five age cohorts to perform the risk analysis and are infants (ages 0 to 1 year), Child 1 (ages 1 to 5 years), Child 2 (ages 6 to 11 years), Child 3 (ages 12 to 19 years) Adult (ages 20 years or older) (US EPA, 1999i; US EPA, 1999j). The distribution of these individuals within the AOI were 8, 64, 69, 69, 316 correspond to infants, child 1, child 2, child 3 and adult, respectively. The variables that describes the human receptor within the 3MRA model are listed in Table 10.

Table 10. Human receptor variables collected for 3MRA

3MRA Variable Code	Variable	Index 1	Index 2	Index 3	Value	Units
NumHumRcpType	Number of residential receptor type				1	unitless
HumRcpType	Type of residential human receptor		NumHumRcpType		Resident	unitless
NumHumRcp	Number of human receptor points at a site				61	unitless
HumRcpPopulation	Human receptor population	NumHumRcp	NumHumRcpType	age cohort (5)	N/A	N/A
NumAquWell	Number of drinking water well				N/A	unitless
AquWellLocation	x, y coordinate of drinking water well	NumAquWell			N/A	N/A
HumRcpAquWellIndex	Index of well used by human receptor	NumHumRcp			N/A	N/A
HumRepAquWellFrac	Fraction of human receptor population on wells	NumHumRcp			N/A	N/A
HumRcpWSSubIndex	Index of watershed occupied by human receptor	NumHumRcp			N/A	N/A
HumRcpLWSIndex	Index of local watershed occupied by human receptor	NumHumRcp			N/A	N/A
HumRcpLWSSubAreal nde	Index of LWS subarea occupied by human receptor	NumHumRcp			N/A	N/A
NumRing	Number of rings to spatially average risk				3	unitless
RingDistance	Distance of ring from WMU	NumRing			500, 1000, 2000	m
RingNumHumRcp	Number of human receptor points in ring	no. of rings (3)			6, 13, 42	unitless
RingHumRcpIndex	Index of human receptor points in ring	no. of rings (3)	RingNumHumRcp		Refer to Appendix	N/A

Block level census attributes are available in 40 different file segments in compressed file format. The file convention used for 39 of the 40 files is ss000yy_uf1.zip, with yy representing values of 01 to 39. The 40th file is the geo header file with a file name ssgeo_uf1.zip. All required information was present in the file named ss00002_uf1.zip. All the uncompressed files are in flat ASCII format. The geographic header file contains information in fixed field format while the other 39 files are in comma-delimited format. Further details about importing data into the template file and linking relevant fields are described in Chapter 7 of the technical documentation in the Summary File 1 of 2000 census of population and housing (US Census Bureau, 2001).

Human receptor point's data were processed using 2000 census block data. Data is assumed to be uniformly distributed within a block polygon. MS Access 2013, Excel 2013 and ArcGIS 10.1 programs were used to process the human receptor data required for 3MRA model. Block census shape file for Yakima County was converted to the UTM Zone 10 coordinate system to be consistent with rest of the data. The rings were split using Erase tool and the census block polygons were clipped using the erased ring polygons. The clipped census polygons were merged to form one file and finally using multipart to single part tool all the multipart features created were separated as individual polygons. The polygon areas were determined using the Calculate Geometry tool in ArcGIS 10.1. The unclipped census block polygon along with 3MRA concentric circles is shown in Figure 14. Clipped and unclipped polygon areas corresponding to each census block were used to calculate the area ratios which were used for area weighting the census parameters. The Calculate geometry tool in ArcGIS 10.1 was used to obtain the centroids for the split polygons to determine the locations of the human receptors. Figure 15 shows the final centroid locations of the processed polygons.

All required STF 1B 1990 block level census parameters listed in Table 9-4 of Section 9.0

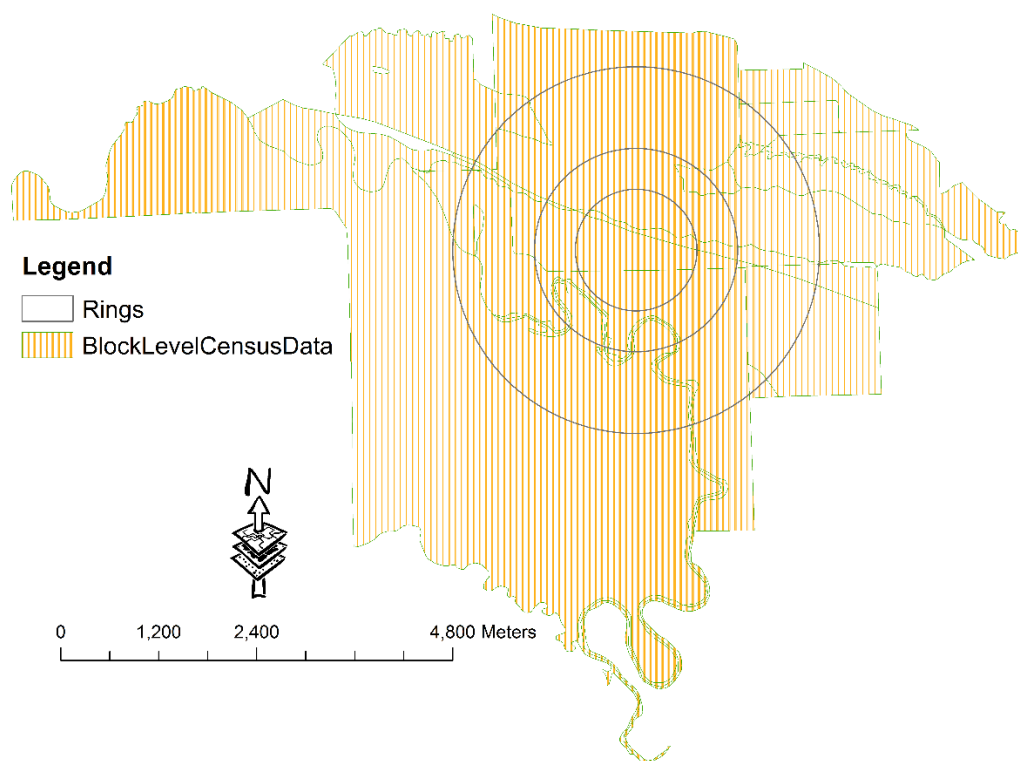


Figure 14. 2000 census block polygons.

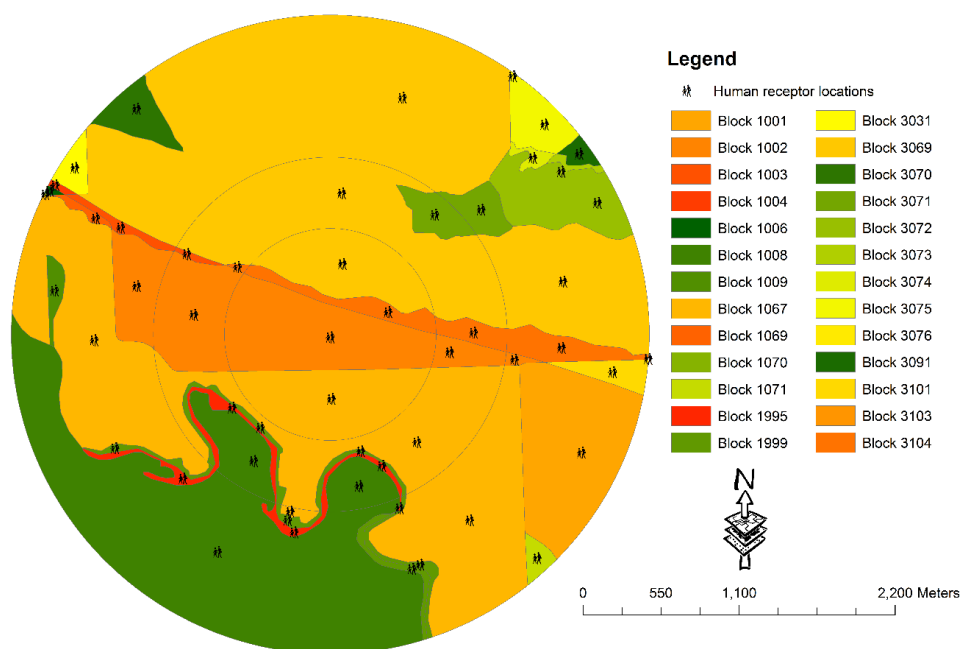


Figure 15. Block census data and the derived human receptor location.

in human receptor data documentation were not available in the same format in SF 1 2000 block level census data (US EPA, 1999j). STF 3 format was changed to SF 3 for 2000 decennial census and field names were not comparable between the two data sets. APPENDIX A – Data Processing Table A - 1 in the Appendix contains the comparable field for 2000 census with the STF-3 data fields. Preprocessing was done to account for changes in reported parameters using MS Access 2013. The logical record number (LOGRECNO) in the geoheader table and the Wa00002.uf1 was used as the primary key to link the tables to form a one to one relationship. Query Design tool was used in MS Access 2013 to facilitate data aggregation of the selected fields after manually selecting the fields based on State, County, County subdivision, census tract, block group, block and finally voting district. The processed fields and filtered data were exported to MS Excel using Export to Excel spreadsheet tool in MS Access 2013. The exported data was converted to dbf file format using Arc Catalog. Joins and Relates tool in Arc Map was used to join clipped data to attribute table. Human receptors are tied to the watershed subbasin and are represented by the variable called HumRcpWSSubIndex in 3MRA site database. HumRcpWSSubIndex is defined in 3MRA as “watershed indices for each human receptor point.” The subbasins shape file was converted to a raster and using the Extract Values to Points tool in ArcGIS 10.1 was used to populate HumRcpWSSubIndex.

Well locations, its use and other characteristics were obtained primarily from biosolids annual reports and Washington State Department of Ecology (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). The well location was digitized using information from the annual reports; however, all other characteristics except water quality information was obtained from Washington State Department of Ecology. The well that is simulated is a drinking water well. The variables describing the human receptor data are listed in Table 10.

3.4.5. Biosolids Characteristics

Biosolids applied to the site during the simulation period originated from two wastewater treatment plants in King County (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). The primary source for biosolids data are the biosolids annual reports submitted to Yakima Health District and were obtained through Freedom of Information Act Requests (FOIA). The two wastewater treatment plants that contribute biosolids that were land applied at the biosolids land application site are West Point Treatment Plant (WPTP) and South Treatment Plant (STP) (King County, 1995). The parameters that describe the characteristics of biosolids and relevant to 3MRA are listed in Table 11. These treatment facilities employ anaerobic digestion to stabilize the solids and reduce odors (King County, 1995). The biosolids are then transferred from King County to storage facilities located near the land application site. The solids content and other parameters could potentially change during this storage and are accounted in the parameter specification for the model by specifying as a uniform distribution. Furthermore, distinction is also not made within the annual reports about the exact origin (WPTP vs. STP) of the biosolids that is applied to a particular land application site (King County, 1995). To account for such paucity in data, distributions were assigned for some of the parameters. For example, pH for the biosolids were assigned a uniform distribution with a range of 7.93 to 8.19 as there was equal likelihood of the biosolids originating from either of the treatment plants.

3.4.6. Soil

The background soil contaminant (total As and total Cd) concentration for the site was obtained from biosolids annual reports submitted to Yakima County Health district using FOIA requests (King County, 1995). The concentration for As was 6.34 µg/g and 4 µg/g for Cd at the

Table 11. Biosolids characteristics

Model Inputs	Code	Units	Data Source/ Processing method	Value/ Distribution
Dry bulk density (biosolids)	BDw	g/cm ³	(Spellman, 1996)	0.8009, Constant 50 lbs./ft ³ for 22 to 30% solids
Settling velocity (suspended solids)	ConVs	m/d	(Proffitt et al., 1993) (Silt, primary particles)	0.29 - 29.29, Uniform
Fraction organic carbon (biosolids)	focW	Mass fraction	(Epstein et al., 1976; Kladvko and Nelson, 1979)	0.235 - 0.194, Uniform
Percent solids (biosolids)	solid	mass percent	(King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999)	e.g., 22%, Constant
silt content (biosolids)	Sw	mass percent	(Jaynes and Zartman, 2005)	60.36, Constant
Biosolids pH	SrcPh	pH units	(King County, 1995; King County, 1996; King County, 1998)	7.93 – 8.19, Uniform

beginning of the simulation and are assumed to be uniform over the entire site in the till zone.

The concentration of B(a)P and DEHP are assumed as zero. Concentrations are not compared for organic constituents due to their unavailability. As Part 503 does not require monitoring of any organic constituents (US EPA, 1993) the soil concentration of organic constituents were not collected by NSF or King County. Surface soil information was collected for watershed subbasins and the biosolids application site. For the purpose of this model surface soil depth is assumed to represent the top 20 cm of the biosolids land application site and 10 cm of for the watershed subbasins. The soil parameters for the AOI was calculated by area and depth weighting. Two categories of data were gathered for this modeling effort. The first set was obtained directly from soil surveys and the second set was derived based on the primary data set. The parameters collected as listed in Table 12.

The soil data set compiled to describe site specific soil properties were obtained from two sources and include, Soil Survey Geographic (SSURGO) Database (NRCS, 2014) and annual reports obtained from Yakima Health District (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). Both spatial and tabular SSURGO data were downloaded for the AOI. The Survey Area Symbol corresponding to the AOI is WA677. The downloaded shape file was clipped for each watershed subbasin, application site and buffer region. Four tables were joined to obtain all the required data, namely; component (Join field: mukey), chorizon (cokey), chtexturegrp (chkey) and chtexture (chtgkey). Clipped polygon areas were calculated and were used in the depth-area weighting calculations. The derived data is processed based on land use information and the primary soil data (Homer et al., 2004).

For each watershed, buffer region and the application site, soil hydrologic group (field name: hydgrp) information was obtained from the component table. The values were area weighted for the AOI and averaged based on the numerical equivalent approach described in

Table 12. Soil data based on module requirements

Variable Name	Description	Data gathering approach	Units
C	USLE cover factor (all subareas except WMU)	derived	unitless
CN	SCS curve number (all subareas except WMU)	derived	unitless
DRZ	Ddepth (root zone, all subareas)	derived	cm
focS	Fraction organic carbon (soil, all subareas)	primary	mass fraction
HydroGroup	Hydrologic soil group	primary	unitless
K	USLE erodibility factor (All subareas except WMU)	derived	kg/m ²
Ksat	Saturated hydraulic conductivity (soil, all subareas)	primary	cm/h
P	USLE erosion control factor (all subareas except WMU)	derived	unitless
POM	Percent Organic Matter	primary	g/g
RHOB	Bulk Density of Soil	primary	g/cm ³
SMb	Soil moisture coefficient b (all subareas)	derived	unitless
SMFC	Soil moisture field capacity (all subareas)	derived	volume %
SMFC	Soil moisture field capacity	derived	volume %
SMWP	Soil moisture wilting point (all subareas)	derived	volume %
SoilType	Soil type for site needed to select correct correlation by soil type	primary	unitless
Ss	Silt content (soil; top 20 cm)	primary	mass percent
WCS	Saturated water content (all subareas, total porosity)	primary	volume fraction
WSPH	Watershed soil pH	primary	pH units

Section 7.0 Soil Data (US EPA, 1999h). Soil map units which did not contain data were substituted with data from largest map unit area. Field capacity and wilting point values were obtained using the lookup table (Carsel et al., 1988) in 3MRA soil data documentation (US EPA, 1999h). Land Cover type and hydrologic condition for the soil were used to derive the SCS curve number values from a lookup table (USDA, 1986). Land cover type definitions in the National Land Cover Database (NLCD) 2001 Version 2.0 dataset along with SSURGO data was used to obtain the Curve Numbers using area weighted approach.

The depth to root zone (DRZ) values were obtained using a lookup table (Dunne and Leopold, 1978) based on vegetation type and soil texture. Deep rooted crop values were chosen as hops are considered to be deep rooted crops (Gingrich et al., 1994).

Table 13 lists the depth to root zone values based on soil textural classification for deep-rooted crops. Each watershed sub-basin, local watershed and the land application site had several map units and correspondingly several textural classes. Hence, area weighted approach was used to compute a representative value for each model unit.

Saturated water content value was also obtained from SSURGO database using area weighted approach and the dry bulk density was calculated using Equation (1). The dry bulk density was only calculated for the land application site. Soil moisture coefficient values were obtained using a lookup table (Clapp and Hornberger, 1978). The soil moisture coefficient values were also area weighted for all the spatial subunits. The table provided in 3MRA soils data

Table 13. Depth to root zone for deep rooted crops (from Dunne and Leopold, 1978)

Soil texture (top 20 cm)	Fine Sand	Fine Sandy Loam	Silt Loam	Clay Loam	Clay
DRZ (m)	1	1	1.25	1	0.67

documentation (US EPA, 1999h) did not include all texture classifications present in SSURGO (NRCS, 2014) and are listed in Table 14.

Fraction organic carbon was calculated using Equation (2)(US EPA, 1996a) as no measured values were available. The representative value of percent organic matter obtained from SSURGO database was divided by 174 to calculate the fraction organic carbon. The values were area weighted. Representative value of soil pH, silt content and USLE erodibility was obtained from SSURGO database using area weighted approach for each individual watershed sub-basin. The USLE cover factors and erosion control factors was obtained using the lookup table given in 3MRA soil data documentation (US EPA, 1999h). The land use codes had to be updated and matched with the NLCD dataset and Table 15 lists the details. The saturated hydraulic conductivity of the top soil (top 20 cm) was based on the lookup table with soil textures obtained from SSURGO database.

$$\text{Dry bulk density} = 2.65 (1 - \text{Saturated water content}) \quad (1)$$

$$\text{fraction organic carbon} = \frac{\text{percent organic matter}}{174} \quad (2)$$

3.4.7. Vadose Zone

Alpha, Beta, WCR and SatK were obtained using the lookup table provided in 3MRA soil documentation based on soil texture data obtained from water well reports. Sand is the predominant soil texture. Table 16 lists the parameters which are based on a national distribution (Carsel and Parrish, 1988).

3.4.8. Chemical Properties

Chemical properties relevant to this study are listed in Table 17 by module requirement and actual values are listed in APPENDIX F – Chemical properties. Effort was made towards

Table 14. Soil moisture based on texture

Soil Texture	Soil moisture coefficient
Sand	4.05
Loamy Fine Sand, Loamy Sand	4.38
Very Fine Sandy Loam, Fine Sandy Loam, Sandy Loam	4.90
Silt Loam	5.30
Loam	5.39
Sandy Clay Loam	7.12
Silty Clay Loam	7.75
Clay Loam	8.52
Sandy Clay	10.4
Silty Clay	10.4
Clay	11.4

Table 15. USLE cover factor (C) and erosion control factor (P)

3MRA land use definition	(Anderson, 1976) code	Compatible NLCD code	C	P
Crop land	82	21, 24	0.08	0.5
Forest land	41	41, 42, 43	0.005	1
Pasture land	81, 52, 71	22, 31, 32, 33, 81, 82, 84, 85	0.01	1
Urban land	21, 22, 23, 24	11, 12, 13, 14, 15, 16, 17	0.01	1
Water	11, 90, 95	51, 52, 53, 54, 61, 62	0	1

Table 16. Vadose zone unsaturated soil hydrologic parameters

Variable	Soil Texture	Min	Max	Transformation	Transformed Mean	Transformed Std. Deviation
Alpha	S	0	0.25	TrnJohnsonSB	0.378	0.439
Beta	S	1.5	4	TrnLogNormal	0.978	0.1
Saturated hydraulic conductivity	S	1e-08	70	TrnJohnsonSB	-0.394	1.15
Residual water content	S	0	0.1	TrnLogNormal	-3.12	0.224

VadThick – constant – 2.5 m

Table 17. Chemical property requirement of modules (subset of Table 17-1 (US EPA, 2003))

Chemical Property	Source Module	Media Modules		CPP
	LAU	Watershed	Vadose Zone Aquifer	
Thermodynamic Properties (Organic chemicals)				
Solubility	*	*	NA	Adj.
Air diffusivity	*	*	NA	Adj.
Water diffusivity	*	*	NA	Adj.
Partition Coefficients (organic Chemicals)				
Henry’s law constant	*	*	NA	Adj.
Soil-water partition coefficient	*	*	*	Adj.
Degradation Constant (Organic Chemicals)				
Hydrolysis rates	*	*	*	Adj.
Aerobic biodegradation rates	*	*	*	Dir.
Anaerobic biodegradation rates	*	*	*	Dir.
Partition Coefficients (metals)				
Partition Coefficients (Biosolids, soil and sediment)	*	*	NA	Dir.
Sorption Isotherms	NA	NA	*	NA

NA – Not applicable

* – Applicable

CPP – Chemical Properties Processor

Adj. – Adjusted for pH and temperature conditions by CPP.

Dir. – Not adjusted and used as is.

Actual values are in the Appendix F

gathering measured data in contrast to calculated and estimated data from biosolids land application studies. The transformations that are accounted in 3MRA model include hydrolysis, anaerobic and aerobic biodegradation for organic chemical constituents (US EPA, 2003). With several studies indicating the dependence of biodegradation constants on sludge organisms, an effort was made to gather data from these studies whenever possible. The chemical parameters required for the simulation are discussed and tabulated for each of the 4 chemicals. Although 3MRA model is distributed by the US EPA with a built in chemical database and contain values for several of the parameters for all four chemicals, most of them were determined to be not appropriate for this study. The data were considered inappropriate for this analysis as the

default dataset did not contain values that were populated from biosolids and biosolids amended soil studies. Example of such inappropriate data include: metal salts studies.

Although studies describing the biodegradation kinetics have documented higher correlations when characterized with the help of a biphasic model. This study does not use a biphasic model for analysis. First-order kinetic expressions were used to describe the initial phase (<40 days) and later stages were being described with fractional power kinetics (Madsen et al., 1999). As the data varies with changes in oxygen availability, microorganisms, initial concentration and temperature, the data reported by Madsen et al. (1999) was not used to build a distribution. Instead, the data was used as individual data point for describing biodegradation kinetics.

3.4.9. Meteorological Data

LAU and all media modules except groundwater require meteorological data and are passed to the model as hourly, daily, monthly, annual and long term data using five files, each representing the five different time scales (US EPA, 1999f). A comprehensive description of the variables in each of these five files are described in detail in the meteorological data collection document. Examples of meteorological data parameters include precipitation amount, wind speed, wind direction, average daily cloud cover and daily average evaporation. Some variables were measured and were available as downloadable data whereas other data were derived using the measured data. Upper air data was obtained from NOAA/ESRL Radiosonde Database and the surface air data was obtained from NCDC. Land use data was obtained from Cropland Data Layer (CDL) (Han et al., 2012).

Two steps were employed to satisfy the meteorological data requirements of 3MRA. The first step involved deriving data that were needed by the model from measured data and

the second step was to process it into 3MRA friendly format. The two steps involved for a successful completion of 3MRA are described here. Hourly data file was processed using surface data and upper air data. Surface data was gathered from National Climatic Data Center (NCDC) as comma separated ASCII format and was processed to SAMSON (Solar and Meteorological Surface Observation Network) format using the NCDC_CNV program. The upper air data is obtained from NOAA/ESRL Radiosonde Database in FSL format (ASCII text) and was processed using the Mixing Height Program to derive the twice daily mixing heights. The meteorological preprocessor PCRAMMET is then used to further process the outputs of NCDC_CNV and the Mixing Height Program to combine the parameters into 3MRA friendly format and data as shown in the Figure 16. The hourly data files are processed further into daily, monthly, annual and long-term data using the procedures described in the meteorological data collection document.

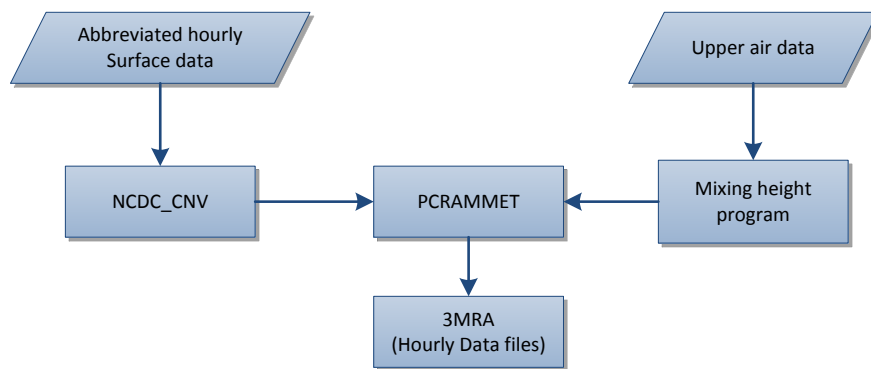


Figure 16. Hourly meteorological data processing.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is divided into nine sections; (i) Calibration and validation (ii) Fate of As and Cd at the biosolids application site (multipathway mass loss) (iii) Long term fate of As and Cd from biosolids applied to till zone (iv) Cancer and non-cancer risk from As and Cd solely from biosolids (v) Groundwater pathway (vi) Importance of buffer strip (vii) Evaluation of non-regulated emerging chemical constituents: B(a)P and DEHP (viii) Comparison of biosolids chemical concentration with food sources and (ix) Implications. The results are described at appropriate sections in the following paragraphs.

4.1. Calibration and Validation

To accomplish calibration and validation of the modified 3MRA model, As and Cd data for biosolids and soil (till zone) are used. Data gathered by Natural Selection Farms, Inc and King County are limited to the regulated pollutants As and Cd in the soil (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999). Organic constituents were measured intermittently in biosolids but were never measured in the soil (till zone). Although, organic constituents were never calibrated for the site, their assessment in a probabilistic sense is assumed to account for their variability. Regulated contaminant measurements in soil are usually only measured when the concentration in biosolids exceed the PC limits listed in Table 1 (US EPA, 1993). However, at Natural Selection Farms, Inc land application sites, soils are being actively monitored for regulated pollutants even though the concentrations in the biosolids are below PC limits.

Figure 17 shows the timeline containing the dates when As and Cd concentrations in the soil were measured as well as the dates when biosolids were applied to the site. In total, there

were 3 biosolids applications to the site at variable application rates and variable heavy metal loading rates in years 1994, 1995 and 1997 (King County, 1995; King County, 1996; King County, 1998). The concentrations of As and Cd were measured in the till zone prior to application in 1994 and 1997 and in the year 1998 (King County, 1995; King County, 1998; King County, 1999). The model was calibrated with the soil measurements for the year 1997 and validated with the measurements from the year 1998 for both As and Cd. It is worth noting that these were the only years where data was made available for this site and had the maximum number of samples. The soil As and Cd concentration data for the year 1994 was used as background concentration as data prior to these years were not available. The source of the background concentration could have been the result of prior applications of fertilizers, pesticides or natural sources (McBride and Spiers, 2001; Fuhrer et al., 2004).

The modified 3MRA model was parameterized with the calibration dataset. The processes accounted by this modified 3MRA model include the following annually variable parameters: (1) biosolids application rates, (2) regulated pollutant loading rates, (3) irrigation

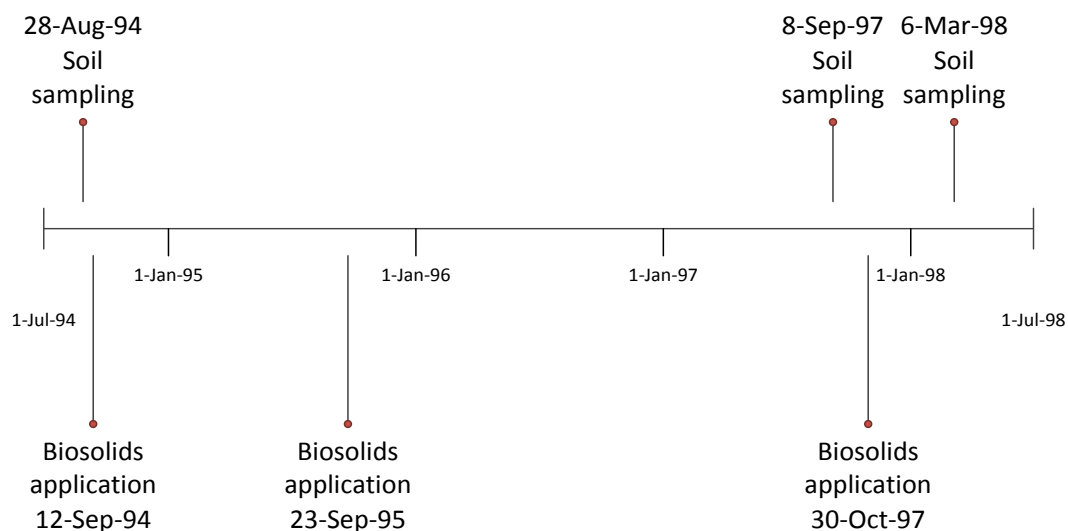


Figure 17. Soil sampling and biosolids application dates for the biosolids land application site. Soil sampling for As and Cd were performed on the same day.

water additions, (4) plant uptake and (5) continued cultivation following termination of biosolids land application (biosolids application cease, but other fertilizer sources are used). The annually variable biosolids application and regulated pollutant loading rates modification to the model is necessary for proper accounting of mass additions to the site. Agriculture in Yakima Valley is primarily realized with irrigation (Vano et al., 2010) and hence, it is critical to account for irrigation water additions. Thus, irrigation and plant uptake were included to account for the mass loss resulting from plant uptake and leaching. Cultivation beyond termination of biosolids application was necessary to account for plant uptake and simulate agricultural activities that occur only in an active site. Such activities will initiate loss of the pollutant through mechanisms such as leaching (from irrigation), erosion from vehicular activity and tillage operations. After accounting for all these additional processes, the modified 3MRA model was implemented in a probabilistic setting with 2000 model runs.

The first transportation mechanism described here is infiltration from the till zone and its behavior for the duration of the simulation is shown in Figure 18. Irrigation water is specified as a constant and hence, there is no variability in the infiltration rate for the simulation period (see Figure 18). On the other hand, Figure 19 contrasts the contribution of precipitation water and irrigation water towards infiltration. It can be observed from the same figure that precipitation water contribution is insignificant as this region is characterized as arid (Vano et al., 2010). Thus, the annual average infiltration rates are primarily the outcome of irrigation water as shown in Figure 19. Irrigation is applied during all four years of simulation although biosolids are only applied during the first two years of the four-year simulation period, as cultivation has continued through the four years of simulation. Irrigation water is applied at

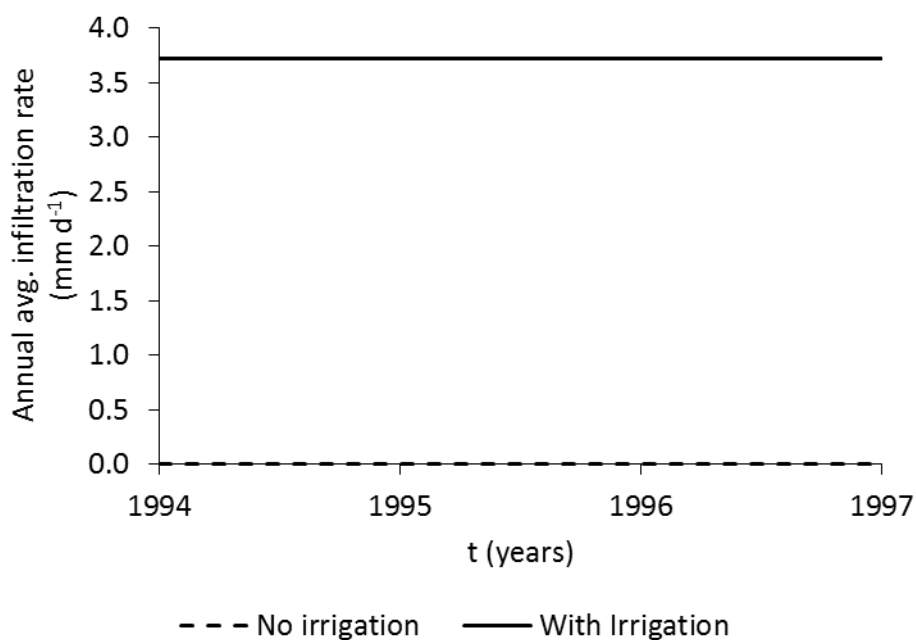


Figure 18. Annual average leachate infiltration rate for the biosolids land application site. Mean value is estimated based on 2000 Monte Carlo realizations. Distribution type for Irrigation is specified as a constant, hence, there is no variability.

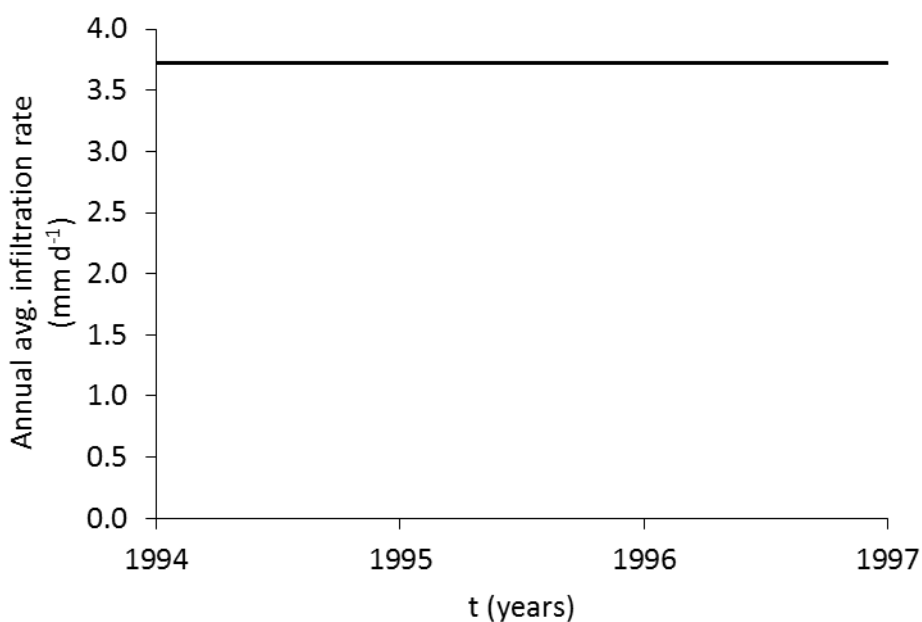


Figure 19. Annual average infiltration rate attributable to the addition of irrigation water in contrast to the no irrigation case (from precipitation). Mean values are estimated based on 2000 Monte Carlo realizations. Distribution type for Irrigation is specified as a constant, hence, there is no variability.

10.33 mm/day, estimated based on uniformly distributing irrigation water demand of 1.27 m (Nakawuka, 2013) for *Humulus lupulus* (hops) for the entire growing season of 123 days (Nakawuka, 2013).

The second transporting mechanism described here is runoff. The chemical constituents are transported by runoff either as dissolved constituent mass or as constituent mass adsorbed to soil or biosolids particles (US EPA, 1999m). Runoff is predicted using the SCS curve number approach (US EPA, 1999m) for the local watershed and all watershed subbasins. As the curve number was specified as a constant there is no variability between predictions. The runoff for the local watershed (area = 620700 m²) is shown in Figure 20. It is the combined flow for the entire watershed subbasin (site and downstream buffer). The Total Suspended Solids (TSS) load to the waterbody is determined using Modified Universal Loss Equation (MUSLE) approach and is shown in Figure 21. The TSS load to the waterbody exhibits the same trend as runoff. The slope of the lines for runoff and TSS are different as parameters used to estimate TSS were specified as a distribution resulting in differences between the two results.

The third transporting mechanism is plant uptake. Plant uptake was applied for all four years of simulation as a loss mechanism as hops were being cultivated during all four years. The plant uptake function removes contaminant from the till zone based on a specified plant uptake coefficient. The plant uptake rates are determined at annual time steps based on the uptake coefficients listed in the technical documentation for Part 503 (US EPA, 1992b). Plant uptake rates specified for As and Cd are 0.001 and 0.008, respectively (US EPA, 1992b) considering biosolids pH in the range of 7.93 to 8.19 (King County, 1995; King County, 1996). Sufficient information in the literature does not exist that quantifies contaminant mass transferred to different parts of the hops plant, although such information does exist for other plant types (US EPA, 1992b).

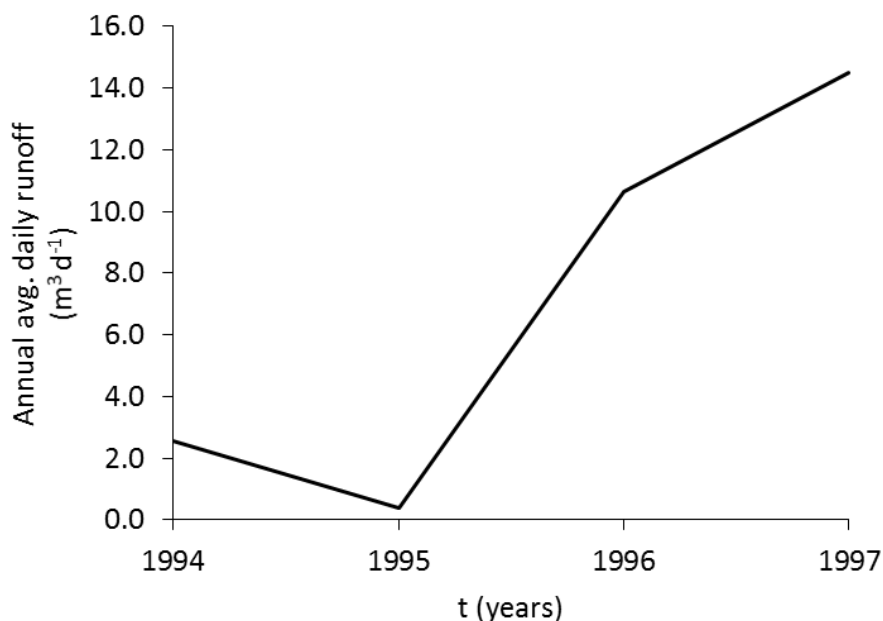


Figure 20. Annual average runoff for the local watershed (watershed containing the biosolids land application site). It is the flow from the biosolids land application site and the buffer regions downstream of the site. Mean, minimum and maximum estimates of runoff are calculated based on 2000 Monte Carlo realizations.

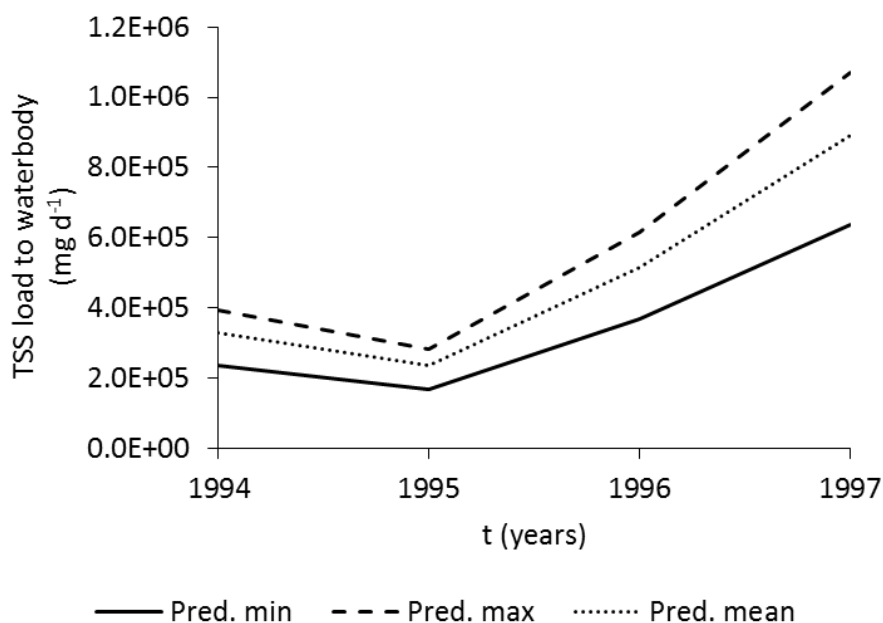


Figure 21. Annual average TSS load to the downstream waterbody. It is the cumulative biosolids/soil load that is eroded from the buffer region and the biosolids land application site. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

Additionally, plant uptake of heavy metals are known to exhibit a plateau effect (Ryan and Chaney, 1994; Hamon et al., 1999) but, this condition is not accounted for here as sufficient information is not available in the reviewed literature to simulate this scenario. Thus, loss due to plant uptake is simulated as mass removed from the soil column at a linear removal rate (for entire plant) based on the concentration of the contaminant in the soil for the particular year under consideration. Plant part based uptake differentiation and plateau effect based differentiation was not simulated. As and Cd uptake by hops exhibit the same decreasing trend like soil concentration of As and Cd in the till zone (see Figure 22).

Different crops have exhibited similar behavior in terms of their response to the concentration of As and Cd in the soil, with higher concentrations in the soil leading to higher uptake and vice-versa (Gaw et al., 2008). Furthermore, As and Cd from aged residues have also remained phytoavailable although there is wide variability in phytoavailability between plant types, soil type, pH, organic matter among others. The trace element concentrations in hops describe the following order $Cd > As$ and this behavior does agree with the work done by other researchers (Gaw et al., 2008). The linear uptake assumption is also reported to be valid in some soil types and plant types (Gray et al., 1999; Gaw et al., 2008). Studies have also demonstrated that addition of biosolids have reduced As uptake from other sources (e.g., chromated copper arsenate (CCA)) (Cao and Ma, 2004).

The fourth mechanism through which the contaminant could leave the till zone is through particulate emissions to the atmosphere (PM₃₀). Particles the size of 30 µm or less are suspended to the air compartment from the site due to the combined effects of vehicular activity, spreading/compacting and tilling activities in addition to wind erosion from an open area (Figure 23). PM₃₀ emissions are predicted to occur in the site for all four years. Inactive years (the last two years - for the purpose of land application) also have emissions as agricultural

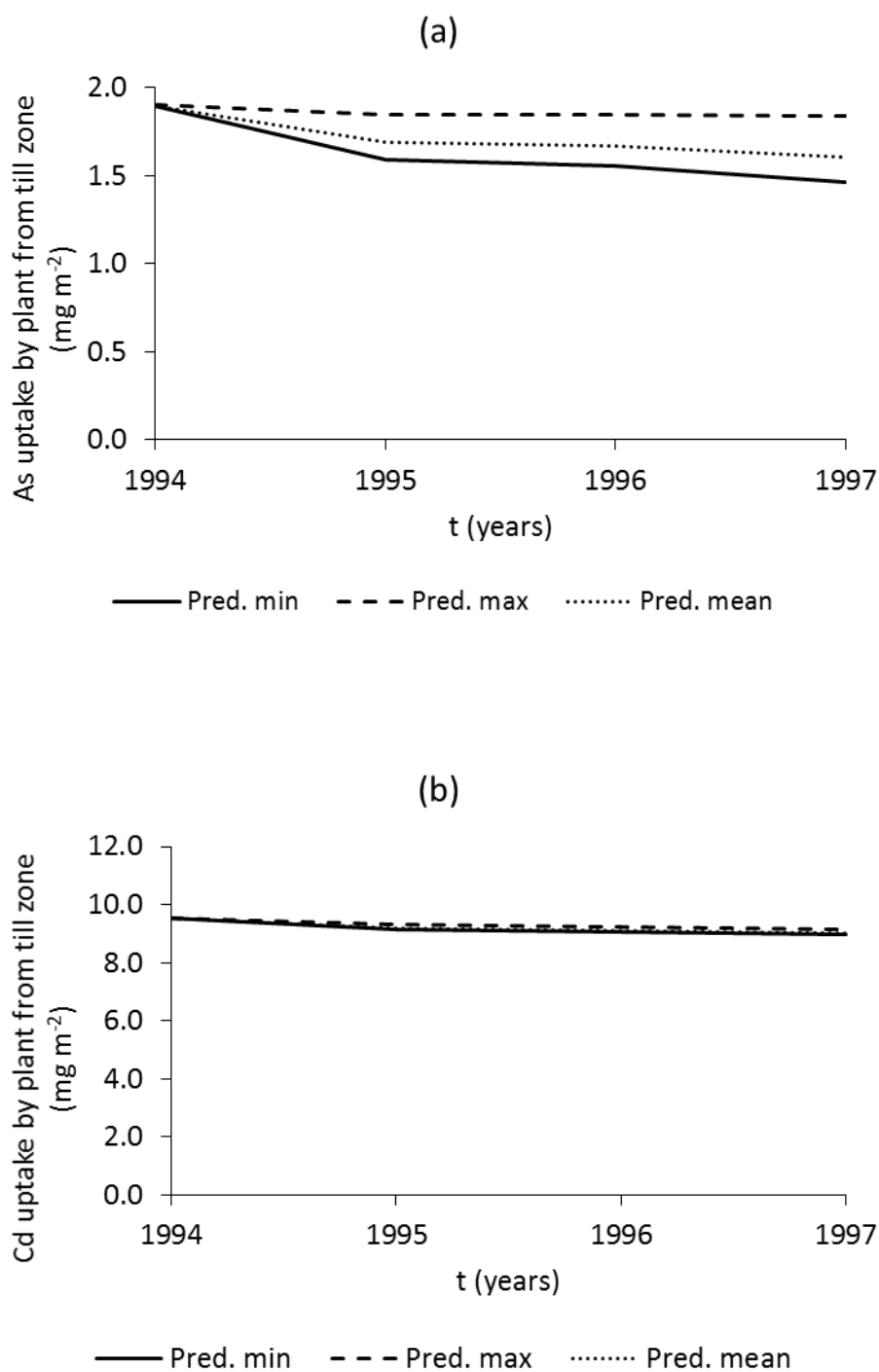


Figure 22. Contaminant mass lost to plant uptake. (a) As and (b) Cd loss predicted using the plant uptake function. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

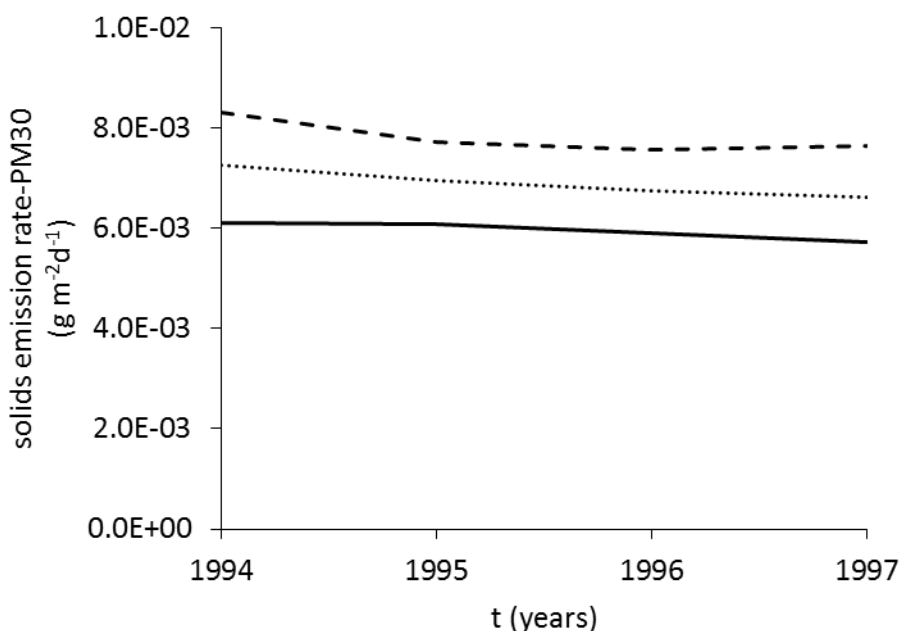


Figure 23. Annual average eroded solids mass emission rate-PM30 (30 μm or smaller particles) from the land application site. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

activities continue for those years as well. The distinction between an active year and inactive year is made based on whether or not biosolids are applied. An immediate decrease in dust emission occurs with fewer field operations as well as when conservation tillage is employed (Baker et al., 2005).

After accounting for all loss processes in the soil column, the depth averaged concentrations of As and Cd for the year 1997 are predicted as 5.12 and 3.77 ($\mu\text{g/g}$), respectively (Figure 24 (a) and (b)). After two years of biosolids application and two years of no biosolids application cultivation, the depth averaged concentration of As and Cd was predicted to decrease in the till zone by 19% and 6%, respectively. It is clear from this effort that both As and Cd mostly remains localized in the till zone where they are initially introduced.

The calibrated model was used with one biosolids application that occurred in the year 1997 to predict the concentration in the till zone for the year 1998 for both As and Cd. Biosolids

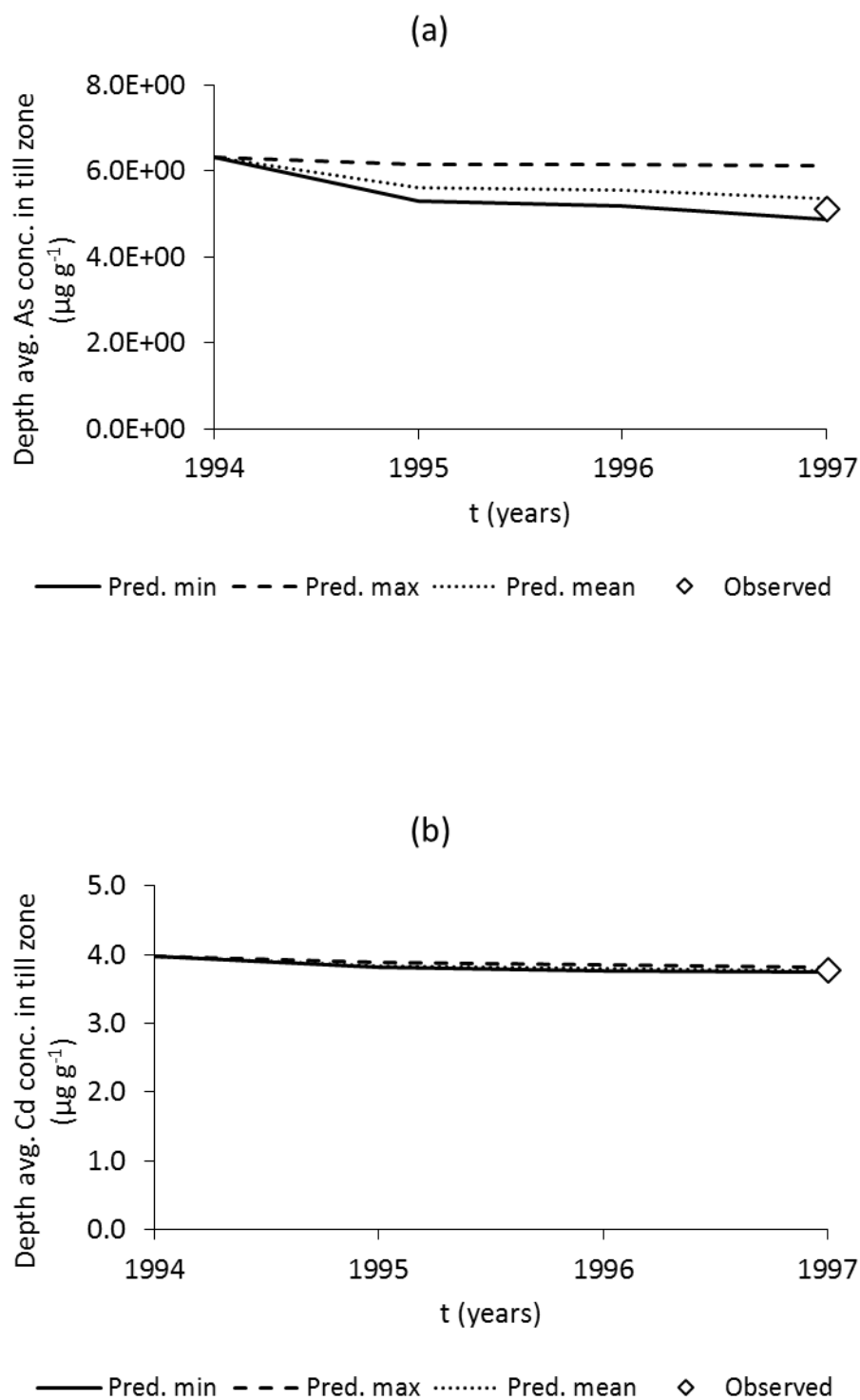


Figure 24. Annually averaged depth averaged concentration in the till zone (a) As and (b) Cd for the biosolids land application site. Mean, minimum and maximum estimates are calculated based on 2000 Monte Carlo realizations.

was applied at 0.006061 Mg/m² with As and Cd concentration of 10.5 mg/kg of biosolids and 5.0 mg/kg of biosolids (DW-basis), respectively (King County, 1998). The model predicted the measured concentration for As and Cd (5.12 of As and 3.77 mg/kg for Cd). This model is now applied to assess and contrast scenarios.

4.2. Fate of As and Cd at the Biosolids Application Site (Multipathway Mass Loss)

The till zone is the primary sink for both As and Cd. The total loss of the As and Cd mass during the four-year period to all loss processes combined is 19 and 6%, respectively. The As mass lost to leaching constitutes only 0.04% of the mass remaining in the till zone. On the other hand, the mass lost due to leaching for Cd is 0.006% of the mass remaining the till zone. The mass lost to plant uptake is 0.4% and 3.3% of the mass remaining in the till zone for As and Cd. The combined mass loss for As is 0.5% for the four years and for Cadmium it is 3.3%. It is higher for Cd as plant uptake coefficient is eight times higher for Cd than for As. The following paragraphs describe the variation of As and Cd lost due to leaching, particulate emissions and to runoff.

On an average, the As and Cd leachate flux exiting the soil column is nearly same for the first two years (Figure 25) and reduces in the next two years. This reduction is attributed to no additional contaminant mass added to the site through biosolids for the remaining two years. However, this reduction represents a very small mass as this pathway itself represents less than 0.04% and 0.006% for As and Cd, respectively, The leachate flux of both As and Cd are a function of the transporter, here, the annual average infiltration rate which is the same due to constant irrigation water application for all four years of simulation.

Total As and Cd load to the downstream waterbody (reach 3. See Figure 13) is calculated as the sum of adsorbed and dissolved fractions and is shown in Figure 26. It follows the same

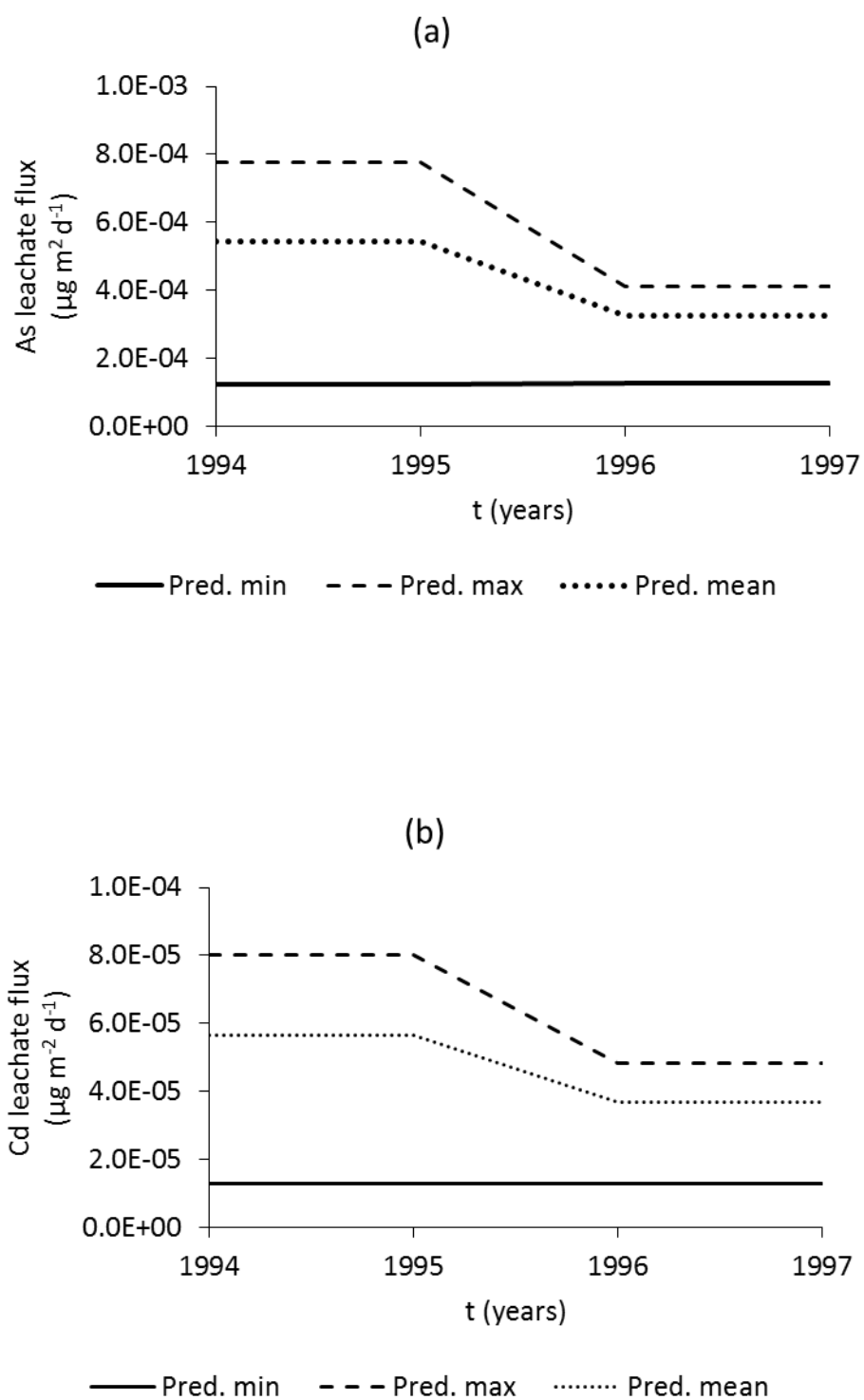


Figure 25. Annual average leachate flux of (a) As and (b) Cd from the land application site. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

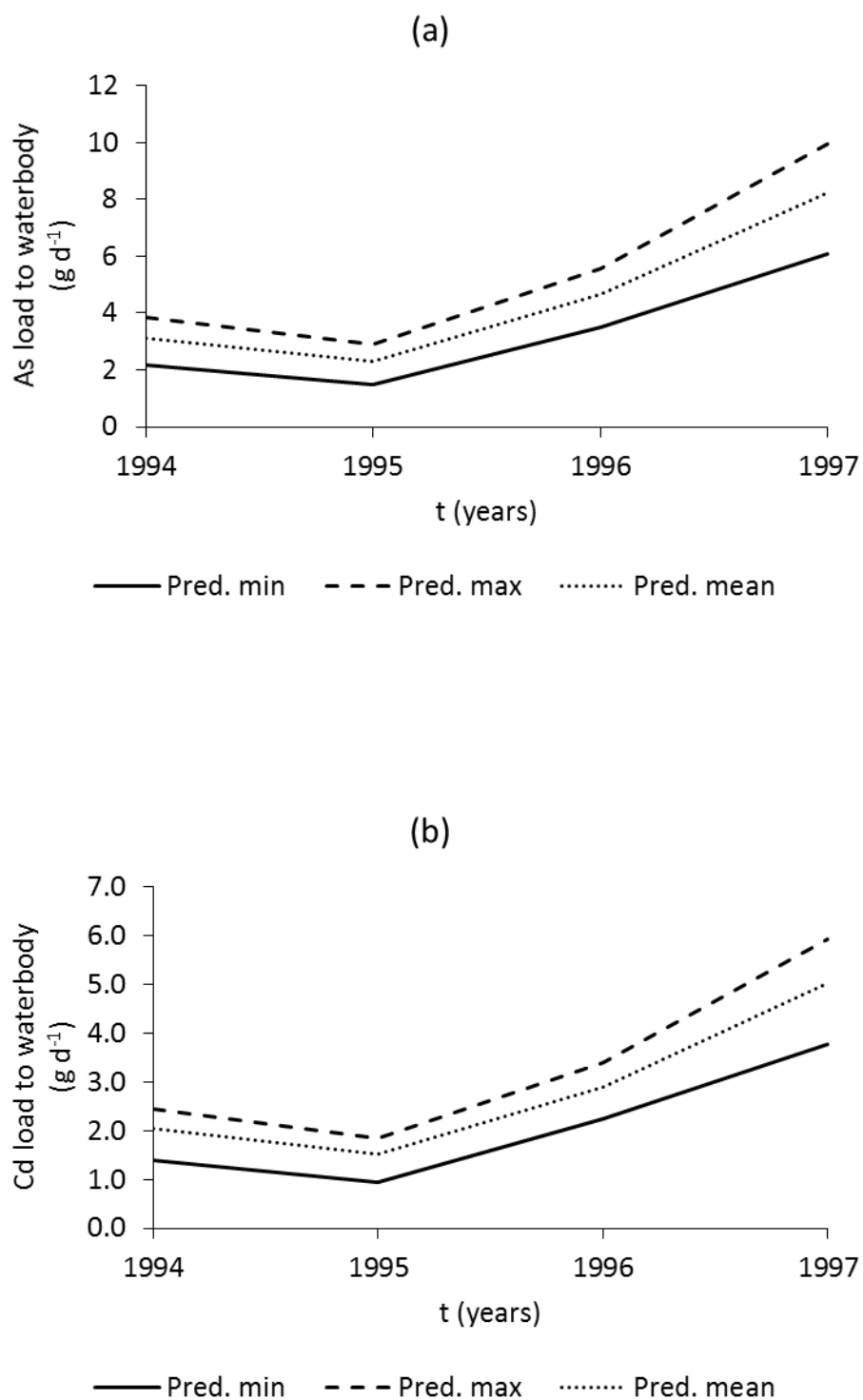


Figure 26. Annual average (a) As and (b) Cd load to the downstream water body from the land application site. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

trend as runoff with higher loads associated with higher runoff years and vice versa. In 3MRA model, the watershed subbasin is subdivided into biosolids application site and buffer regions (upper and lower) (US EPA, 1999m). In this case, the watershed subbasin contains the land application site and the region from the downstream boundary of the site to the drainage divide called as buffer region (i.e., region between the site and reach 3). This region receives As and Cd loads transported by runoff from the site. Thus, As and Cd load to reach 3 is contributed from the buffer region. The As load to reach 3 is slightly higher than Cd load; however, the mass being lost through this pathway represents less than $8 \times 10^{-9}\%$ and $1 \times 10^{-9}\%$ for As and Cd mass present in the till zone, respectively.

The As and Cd adsorbed to soil and biosolids particles are suspended by vehicular activities at the site (Figure 27). The As and Cd associated with the soil displays a decreasing trend as there is less contaminant mass available in the till zone for loss through this pathway. The loss of As and Cd introduced from biosolids that are land applied or other agricultural operations through particulate emission from the field are reported by other authors (Vega et al., 2001; Chow et al., 2003; Bhat and Kumar, 2013). As and Cd released from the land application site in the form of particulate emissions are deposited within the AOI as wet (particles and vapors) or dry (particles only) deposition and the values are calculated for the top 1cm of the soil (US EPA, 1999o). The contaminants are then subjected to transport processes such as leaching, runoff and erosion and the resulting concentrations at annual time steps are shown in Figure 28 and Figure 29. The watershed subbasin that contains the site is the most polluted. The smallest spatial discretization in 3MRA is the watershed subbasin and the concentrations are estimated only at the human receptor locations and averaged for the entire subbasin. Thus, elongated watersheds will not capture the concentrations appropriately. The

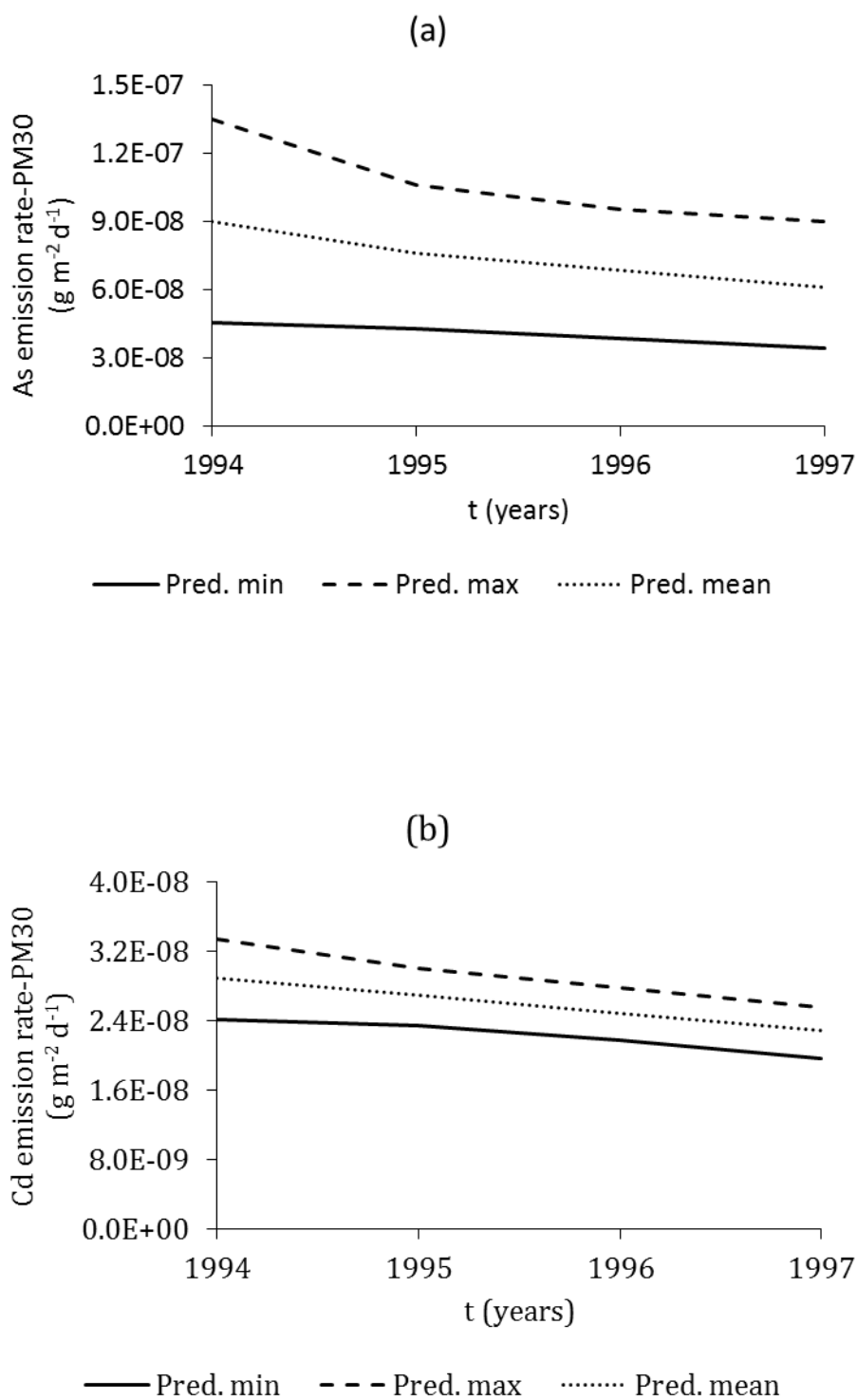


Figure 27. Annual average (a) As and (b) Cd mass flux of $30 \mu\text{m}$ or smaller particles (PM30) released from the land application site. Years 1996 and 1997 have no emissions. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

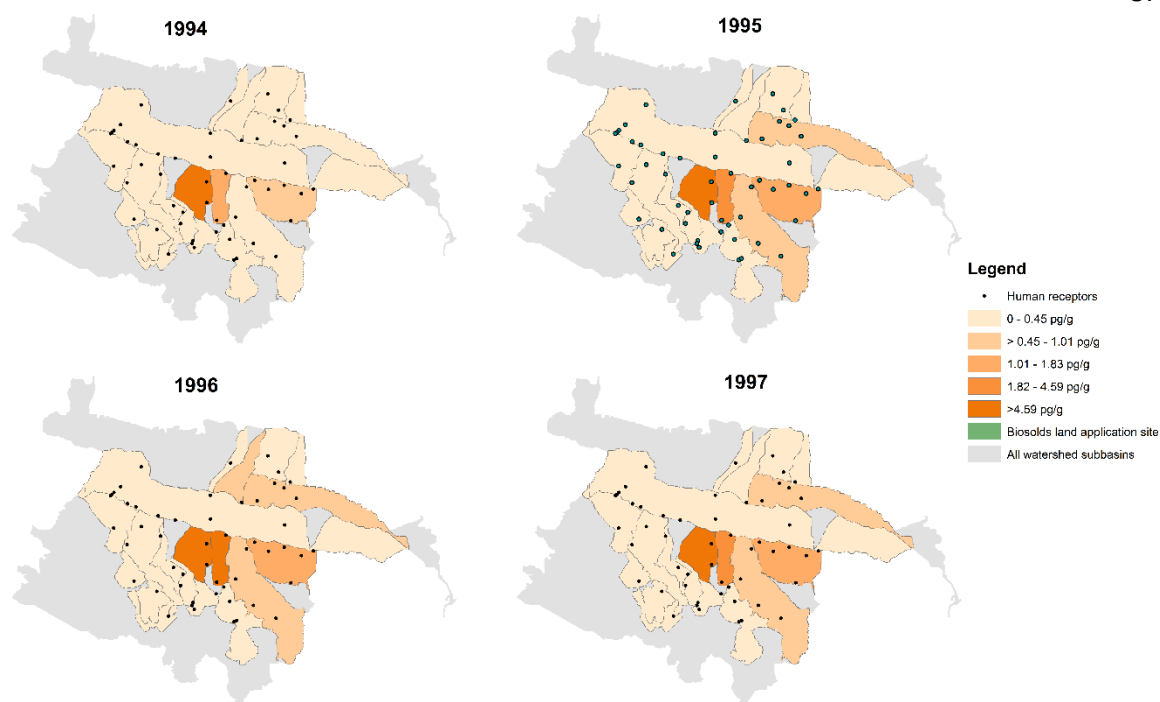


Figure 28. Annually averaged depth averaged soil concentration of As in pg/g (in top 1 cm of soil) for watershed subbasins. The concentrations in each subbasins for each year are the outcome of aerial deposition, erosion and runoff from upstream subbasins and waterbodies and loss processes (erosion and leaching).

concentration in the surficial soils for the entire watershed is higher for Cd as the soil-water distribution coefficients are higher than As.

The concentration of As and Cd in all the reaches within the AOI were estimated. From the 48 reaches (which includes the Yakima River) that were assessed only four reaches had non-zero As and Cd concentration (see Figure 30). Furthermore, from these four reaches, only reach number 3 (see Figure 13), situated directly downstream from the site, receives As and Cd loads that exceed the EPA water quality standards. The concentration of As in reach 3 varies from 0.01 mg/l to 0.02 mg/L and that of Cd from 0.007 mg/l to 0.01 mg/l from year 1994 to 1997 (Figure 30). In terms of both As (0.01 mg/l) and Cd (0.005 mg/l) the US EPA drinking water criteria was not satisfied if undiluted flows are considered. On the other hand, it does satisfy the acute

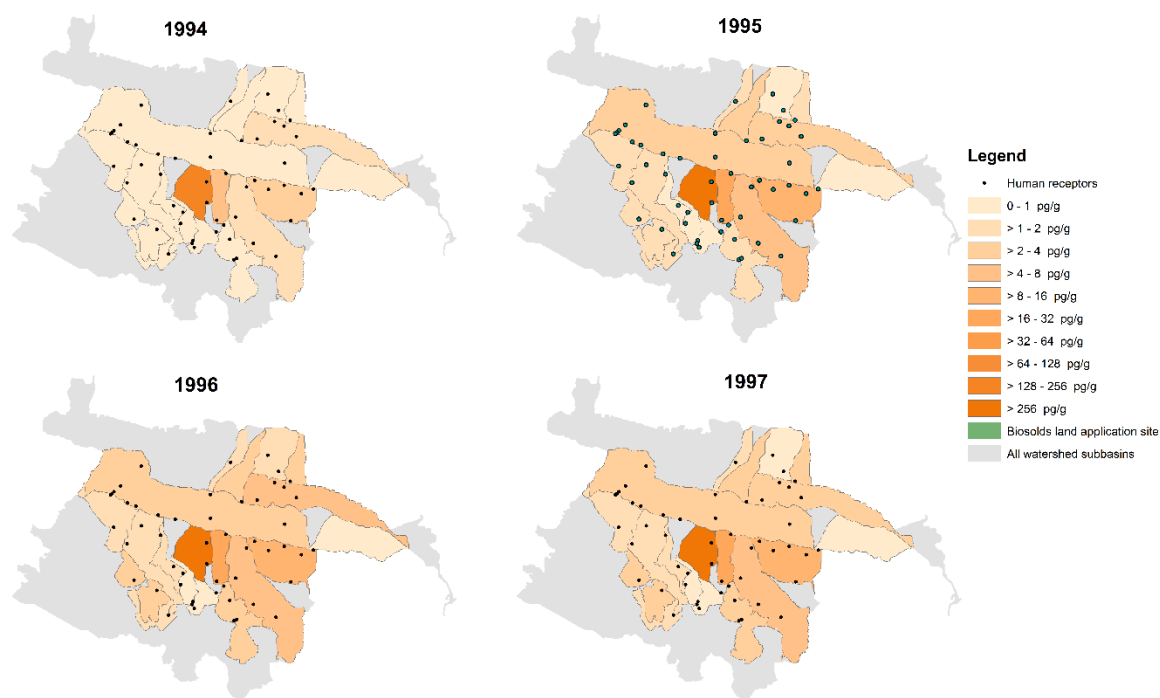


Figure 29. Annually averaged depth averaged soil concentration of Cd in pg/g (in top 1 cm of soil) for watershed subbasins. The concentrations in each subbasins for each year are the outcome of aerial deposition, erosion and runoff from upstream subbasins and waterbodies and loss processes (erosion and leaching).

aquatic life US EPA criteria for As (0.34 mg/l) but not for Cd (0.002 mg/l). The smallest spatial unit is the entire reach and no sub-discretization is modeled by 3MRA. In other words, the change in concentration from one section of the reach to another (longitudinal variation) is not modeled.

This flow in this reach is very small in comparison to the Yakima River and only represents 0.03% of the minimum flow of the Yakima River for the last 50 years. Therefore, the concentration of As and Cd load from reach 3) in the Yakima River are likely to be very small because of dilution. This increased predicted concentration in reach 3 is primarily due to background concentration and not from the two years of biosolids application (see long-term fate of As and Cd from biosolids applied to till zone section).

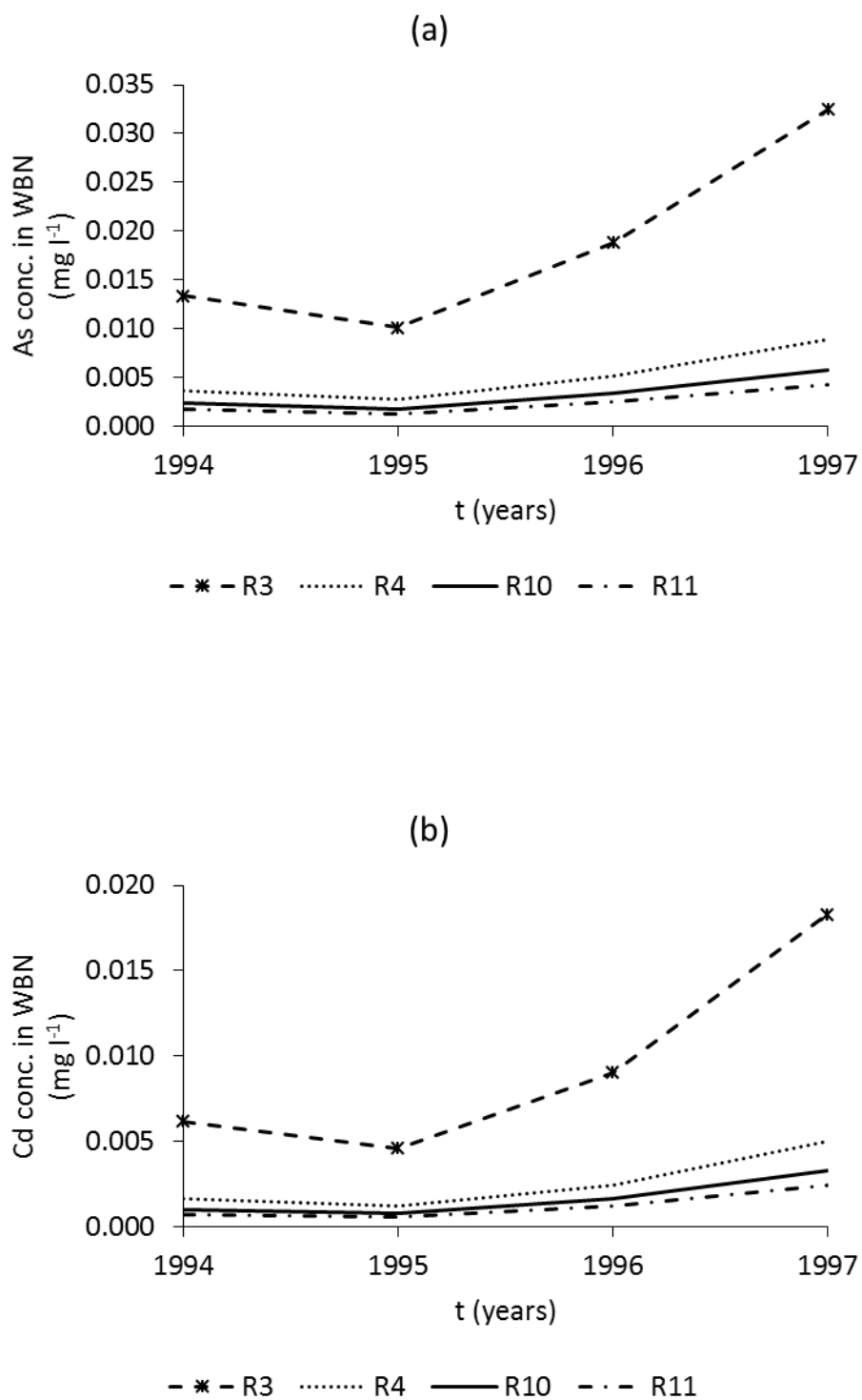


Figure 30. Total (a) As and (b) Cd concentration in the water column in the reach downstream of the site. Mean, minimum and maximum estimates are determined based on 2000 Monte Carlo realizations.

The cancer risk and the Hazard Quotient (HQ) are determined for residential receptors located within the AOI and are differentiated by age cohorts, exposure pathways, receptor location and exposure period. Five age cohorts are considered and eight exposure pathways were assessed. Four of the eight pathways are aggregated estimates and include, (1) exposure from all inhalation pathways, (2) all ingestion pathways, (3) all groundwater pathways and (4) all ingestion and inhalation pathways (see site layout section). The risk estimate is determined based on the timing of the maximum risk and provides information about the exposure period of greatest risk differentiated based on age cohorts and location.

A residential receptor is exposed only to inhalation via air and shower and ingestion via soil and water (US EPA, 1999b). Exposure through shower is estimated only for adults and children between ages 12 to 19 years. It is important to note that exposure through shower is the only pathway that is not modeled for all age cohorts. The results are aggregated based on age cohort, 3MRA rings, exposure pathway and route. For example, aggregation of exposure route indicates all exposures that occur through the same portal of entry such as ingestion. On the other hand, pathway based aggregation is, for example, aggregation of all exposures from groundwater pathway (i.e., drinking water ingestion and shower inhalation).

The cancer and non-cancer risk (HQ) resulting from the combined effects of background concentration and that introduced from biosolids land application is listed in Table D - 1 and Table D - 2 in APPENDIX D – Cancer and non-cancer risk from four pathways. From the four pathways that were evaluated, namely; air inhalation, water ingestion, soil ingestion and inhalation from showering, three pathways did not present any unacceptable excess cancer risk or greater than 1 HQ from the combined effects of background soil concentration and biosolids activities. Furthermore, the HQ values were below 1 for all pathways of exposure including ingesting contaminated soil (see Figure 31). The only pathway that presented an incremental

unacceptable cancer risk (one additional case of cancer during a lifetime in a population of a million people) is the soil ingestion pathway and for age groups 1 to 5, 6 to 11 years and for 12 to 19 years (see Figure 32). The 1 to 11 age group is considered to ingest soil from behavioral (not washing hand properly or eating dirt) activities common to this group and adults are considered to ingest soil from gardening or work related activities (US EPA, 1999b; US EPA, 1999c). The base 3MRA model only estimates incremental cancer risk from biosolids land application activity, here the background soil concentration is also accounted for. However, this does not represent the risk from all pathways and processes a human receptor may be exposed to.

There is no risk from Cd through the soil ingestion pathway; however, there is elevated levels of risk resulting from As through the same pathway (greater than 1×10^{-6}). There is no risk estimate for Cd as the Cancer Slope Factor (CSF) is not available (US EPA, 1999k). Age specific distinction is not made for CSF value specification as CSF values are not available for the different age groups. The differentiation between the origin of the risk (from background soil concentration or from biosolids land application practice) is covered in the section Cancer and non-cancer risk from As and Cd solely from biosolids.

4.3. Long-Term Fate of As and Cd from Biosolids Applied to Till Zone

From the four age groups evaluated in the risk assessment within the AOI, three of them exceeded the acceptable risk criteria of one additional case of cancer during a lifetime in a population of a million people. Both As and Cd exhibited similar risk outcomes for the four-year simulation. This incremental risk estimate could have been the outcome of either the background soil concentration or from land application of biosolids. In order to determine the source of this risk a scenario involving biosolids land application is assessed without considering

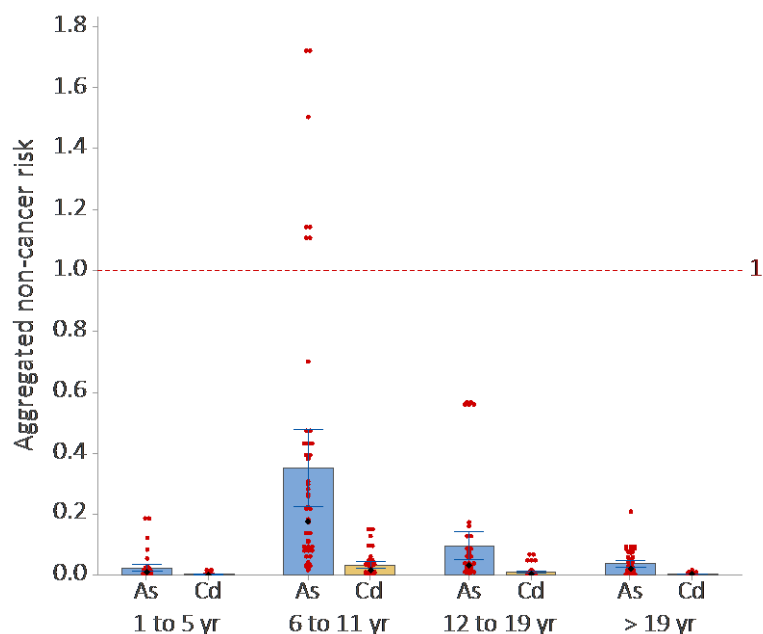


Figure 31. Aggregated non-cancer risk (Ring 1 = 500m) resulting from the combined effects of background concentration and biosolids land application activities through ingestion of contaminated soil. Detailed description of age cohorts is provided in APPENDIX D – Cancer and non-cancer risk from four pathways. Error bars represent standard deviation and dots represent individual values.

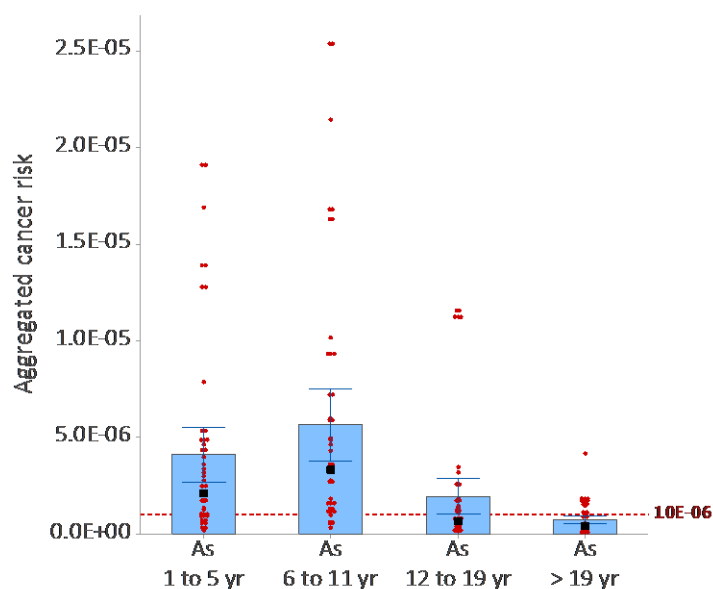


Figure 32. Aggregated cancer risk (Ring 1 = 500m) resulting from the combined effects of background concentration and biosolids land application activities through ingestion of soil contaminated with As. Detailed description of age cohorts is provided in APPENDIX D – Cancer and non-cancer risk from four pathways. Acceptable risk corresponds to one additional case of cancer during a lifetime in a population of a million people. Error bars represent standard deviation and dots represent individual values.

background concentration. Therefore, to isolate the risk solely from the land application practice a consecutive multi-year application scenario is evaluated at agronomic rates and at the maximum allowable regulated pollutant loading rates for both As and Cd. This assessment considers that the site will receive biosolids only for 20 years, which is similar to the assumption in the Part 503 risk assessments (US EPA, 1992a; US EPA, 1992b).

For this scenario a biosolids application rate of 0.001481 Mg/m² and solids content of 22% was considered. The loading rates for the chemical constituents are 75 and 85 mg/kg of biosolids on a dry weight basis for As and Cd, respectively. The 20 year application is followed by 80 years of no application although cultivation (agricultural activities) does continue during the entire simulation period (100 years). This modification to the model will not only account for uptake by plants, but will ensure that irrigation water additions and loss through emissions from agricultural activities are accounted during the entire simulation period.

The results show a continuous increase in As and Cd concentration in the soil column during the 20 year consecutive application period (Figure 33). Such behaviors are reported for regulated metals present in biosolids, such as for Cu and Zn (Sukkariyah B, 2007). Cd is considered to accumulate at the point of introduction into the soil and concentrations are known to increase with repeat applications (Bergkvist et al., 2003). Sludge bound metals (including Cd) were not found beyond the 20 cm depth in silt loam soil (Yingming and Corey, 1993). Shorter terms (e.g. 9 years) studies have strongly supported no movement beyond the till zone (Williams et al., 1987).

Following termination of land application at year 20, a steady decline in the Cd concentration in the till zone is observed and at year 100 the concentration drops by 57% of the peak concentration (peak concentration is at year 20). Evidence of metal translocation by leaching beyond the till zone have been noted in longer term studies (Joshua et al., 1998)

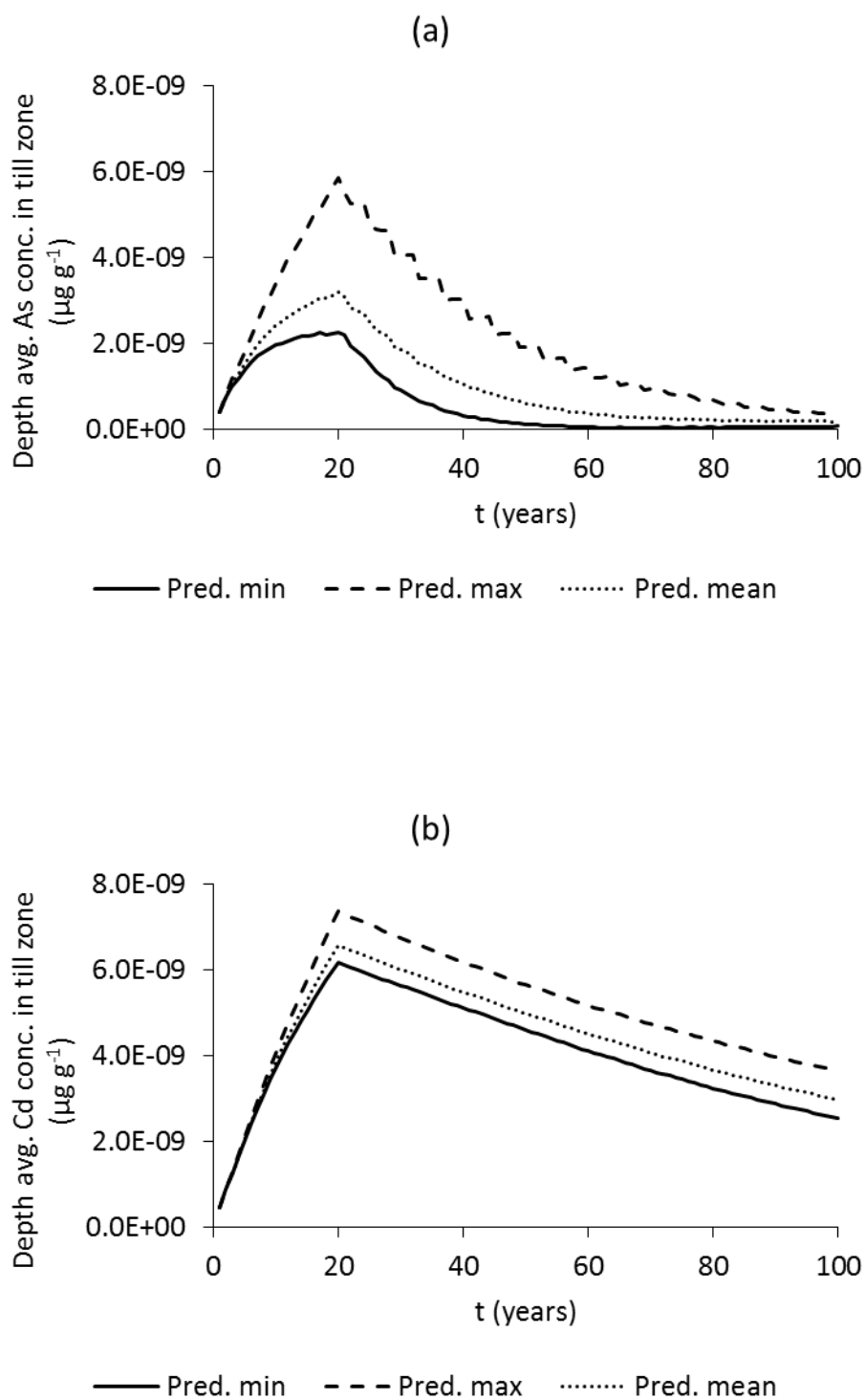


Figure 33. Depth averaged (a) As and (b) Cd concentration in the till zone for 20 years of consecutive biosolids application followed by no biosolids application cultivation. Predicted minimum, maximum and mean were estimated from 2000 Monte Carlo realizations.

showing such mechanisms do play a role; however, minor. The 43% loss of Cd from the soil column during this period (at year 100) can be attributed to the combined effects of leaching, plant uptake, particulate emissions and transport through surface runoff (sheet flow).

The As concentration in the soil column increases from year 1 to year 20 and reduces from year 20 onwards. At year 77 the concentration is zero (see Figure 34). Similar to Cd, As reached a maximum concentration in year 20, the last year of biosolids application considered in the simulation. However, unlike Cd, As concentration dropped to zero in the year 77 (Figure 33). The primary difference in the behaviors between the As and Cd in the context of the transfer from the till zone is the solid-solution partition coefficient.

While Cd concentration is decreasing in the till zone its concentration in the buffer region increases (Figure 35 a). This increase in the concentration is observed until year 80, after which the concentration does not increase any further. It can be inferred that after several years, the buffer region itself can serve as the primary source for a contaminant (here Cd). As concentration in the buffer region, like Cd begins to increase; however, unlike Cd, its concentration begins to reduce after year 38 (Figure 35 b).

The soil column profile plot for As (Figure 34) illustrates the change in the concentration for the 1 cm soil column cells (layers, total = 20 layers). The concentration in upper most cell is higher as the diffusive mass flux estimated are added back to the top layer. This is performed as it is assumed that contaminant mass is not lost due to aqueous diffusion from the top boundary of the soil column (till zone). This treatment is required to avoid non-volatile contaminants (such as both As and Cd) to be erroneously be removed from the soil column. The air to water ratio is relatively constant within the till zone; however, at the soil column-air interface this assumption does not hold good (US EPA, 1999m). Limited translocation of heavy metals introduced from biosolids have been reported from field studies (Sukkariyah B, 2007). For example, the

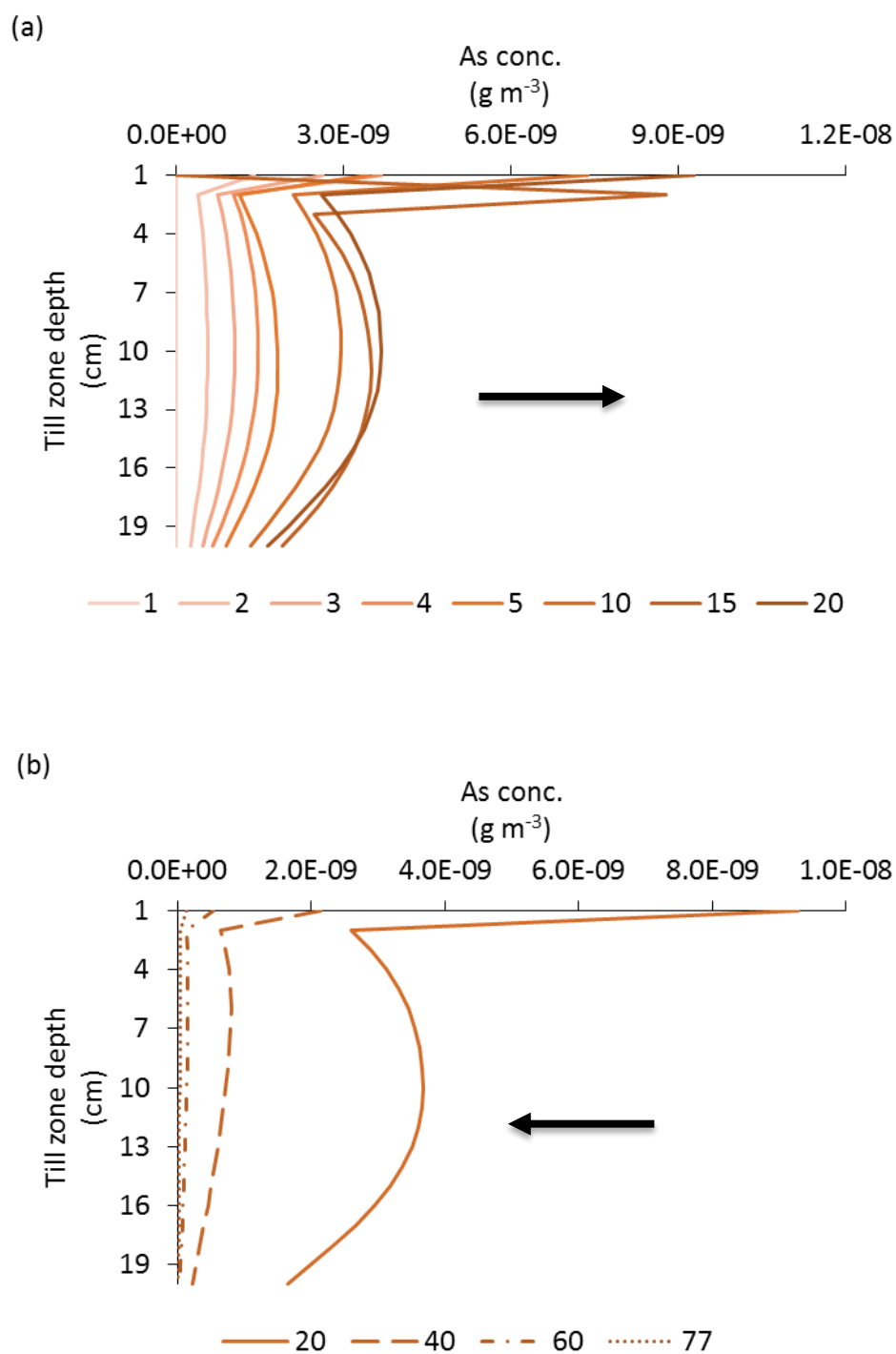


Figure 34. Variation in As concentration in the soil column (a) from year 1 to 20, direction of arrow shows concentration increasing in the soil column and (b) from year 20 to 77, direction of arrow shows concentration decreasing in the soil column. Predicted mean was calculated from 2000 Monte Carlo realizations.

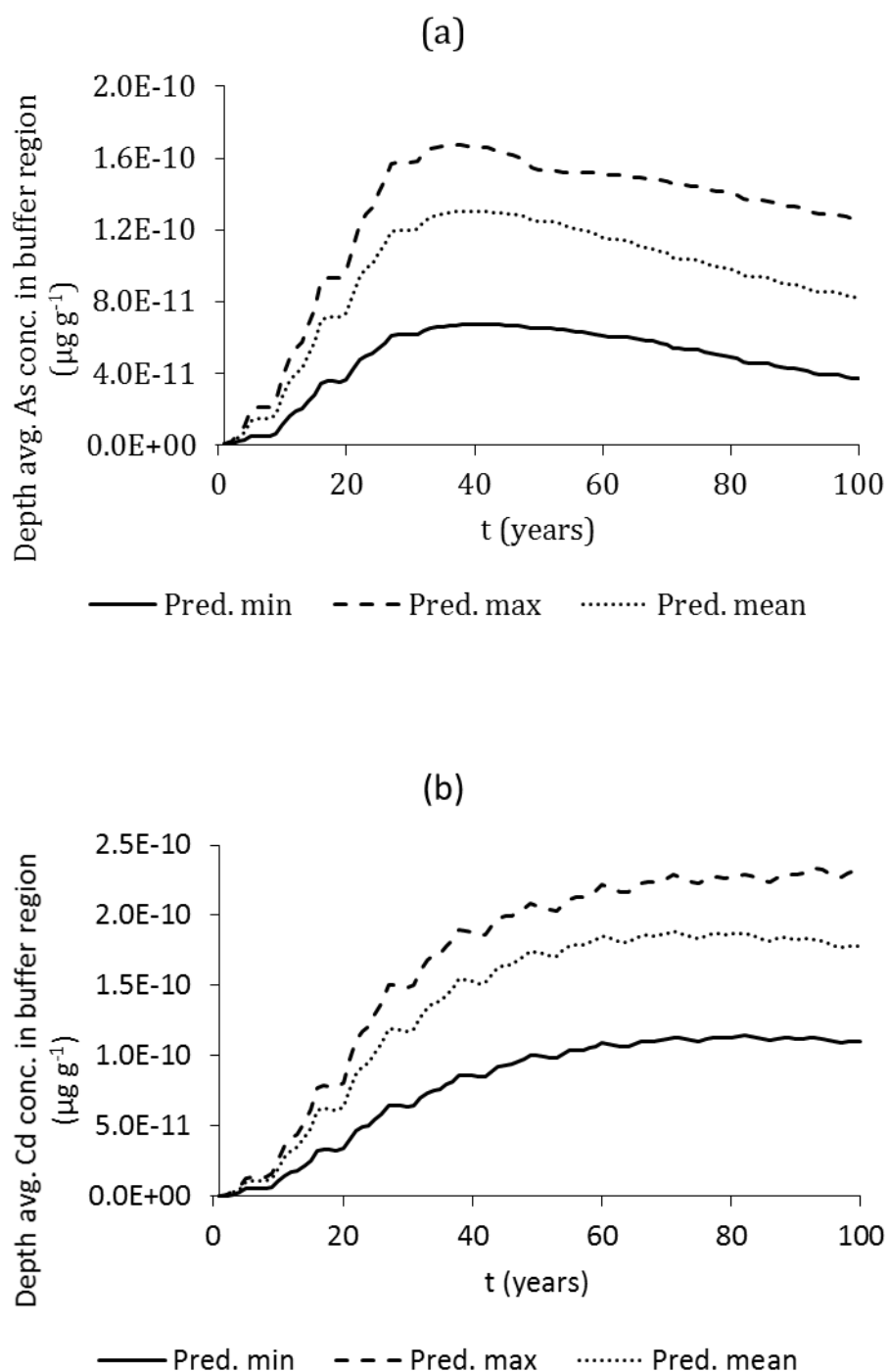


Figure 35. Depth averaged (a) As and (b) Cd concentration in the buffer region for 20 years of consecutive biosolids application followed by no biosolids application cultivation. Predicted minimum, maximum and mean were estimated from 2000 Monte Carlo realizations.

vertical soil profiles for biosolids amended soils (silt loam) showed Cu and Zn remained mostly in the top 15 cm with negligible transfer below the till zone (≈ 0.2 m) (Sukkariyah B, 2007). The general trend of the As curve for the till zone is shown Figure 34 agrees with another site.

During the first 20 years, the rate of Cd mass flux adsorbed to $30\text{ }\mu\text{m}$ or smaller particles (PM₃₀) released from the land application site continues to rise and is attributed to vehicular activity (Figure 36). The total particulate emission from a biosolids land application site is the outcome of wind erosion, vehicular activity and spreading/compacting or tilling operations (US EPA, 1999m). The PM₃₀ emission rates remain constant during the 20-year period; however, the concentration of Cd increases in the till zone during the same period. The amount of biosolids applied to every square m of the site is 1.48 kg and distribution of particles equal to $10\text{ }\mu\text{m}$ or smaller is 61%. Therefore, the PM₁₀ particles emission rate for every kg of biosolids applied is 2.8 mg which is in the range (7.6 ± 6.3 mg/kg of biosolids) reported by other researchers (Paez-Rubio et al., 2007).

The infiltration rate is dominated by irrigation water and does not vary during the entire period of simulation. Cd leaching through the bottom layer of the till zone continues to increase till year 20 and concentration begins to reduce (Figure 37). This trend can be attributed to the rise in the Cd mass available for leaching in the till zone each year with repeat applications which is followed by decrease in Cd concentration. At year 20, the concentration of Cd in the leachate is 8.8×10^{-9} $\mu\text{g/l}$. The increase in leachate concentration with increased concentration in the soil is also reported by other researchers as well (Keller et al., 2002). However, the mass lost due to this pathway does not seem to be significant, similar observations were noted by other researchers (Brown et al., 1983). It was also shown that in the 20 years, approximately 1% of the metals applied through biosolids moved beneath the plough layer (McGrath and Lane, 1989),

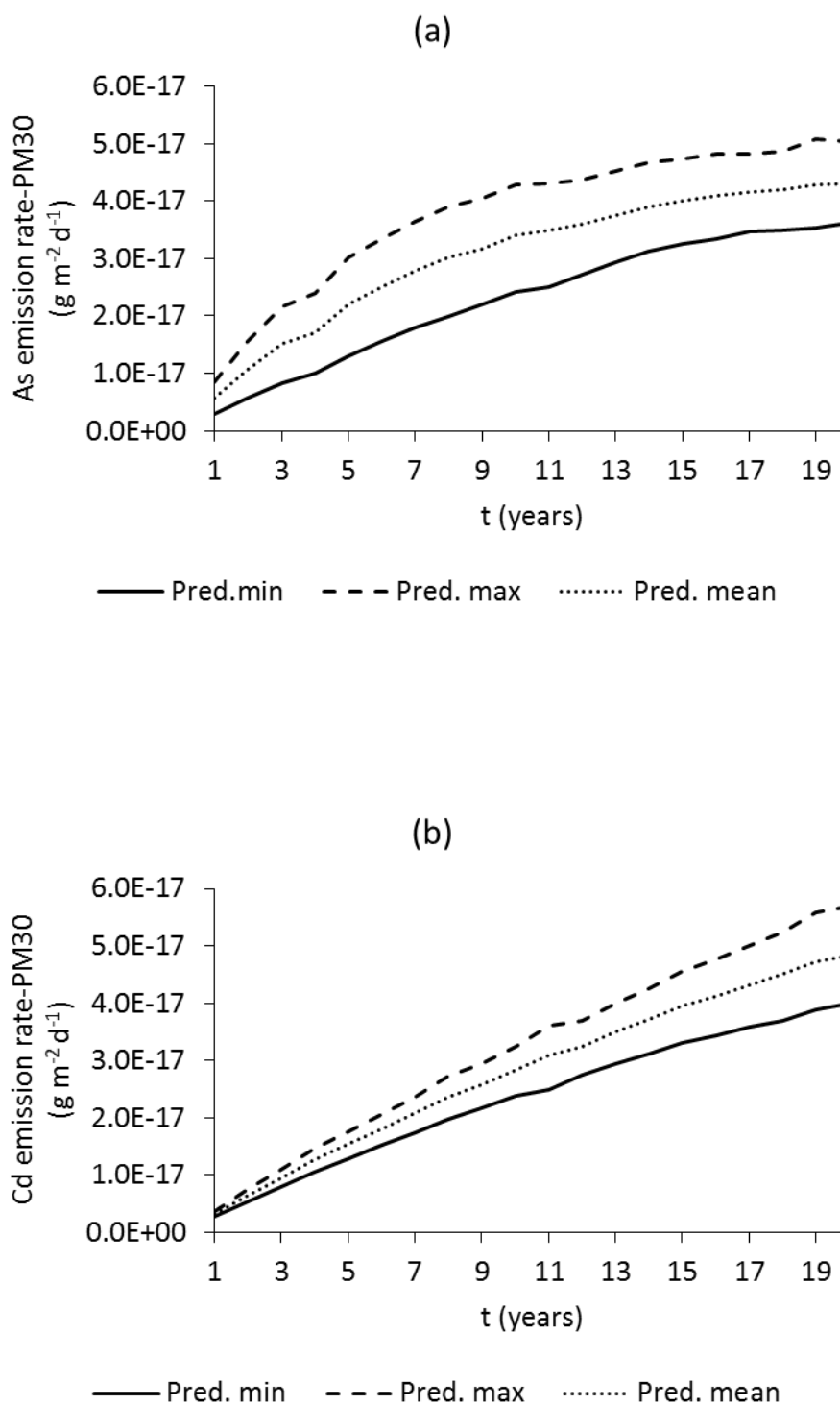


Figure 36. Emission rates of As and Cd adsorbed to particles 30 μm or less. Predicted minimum, maximum and mean were calculated from 2000 Monte Carlo realizations.

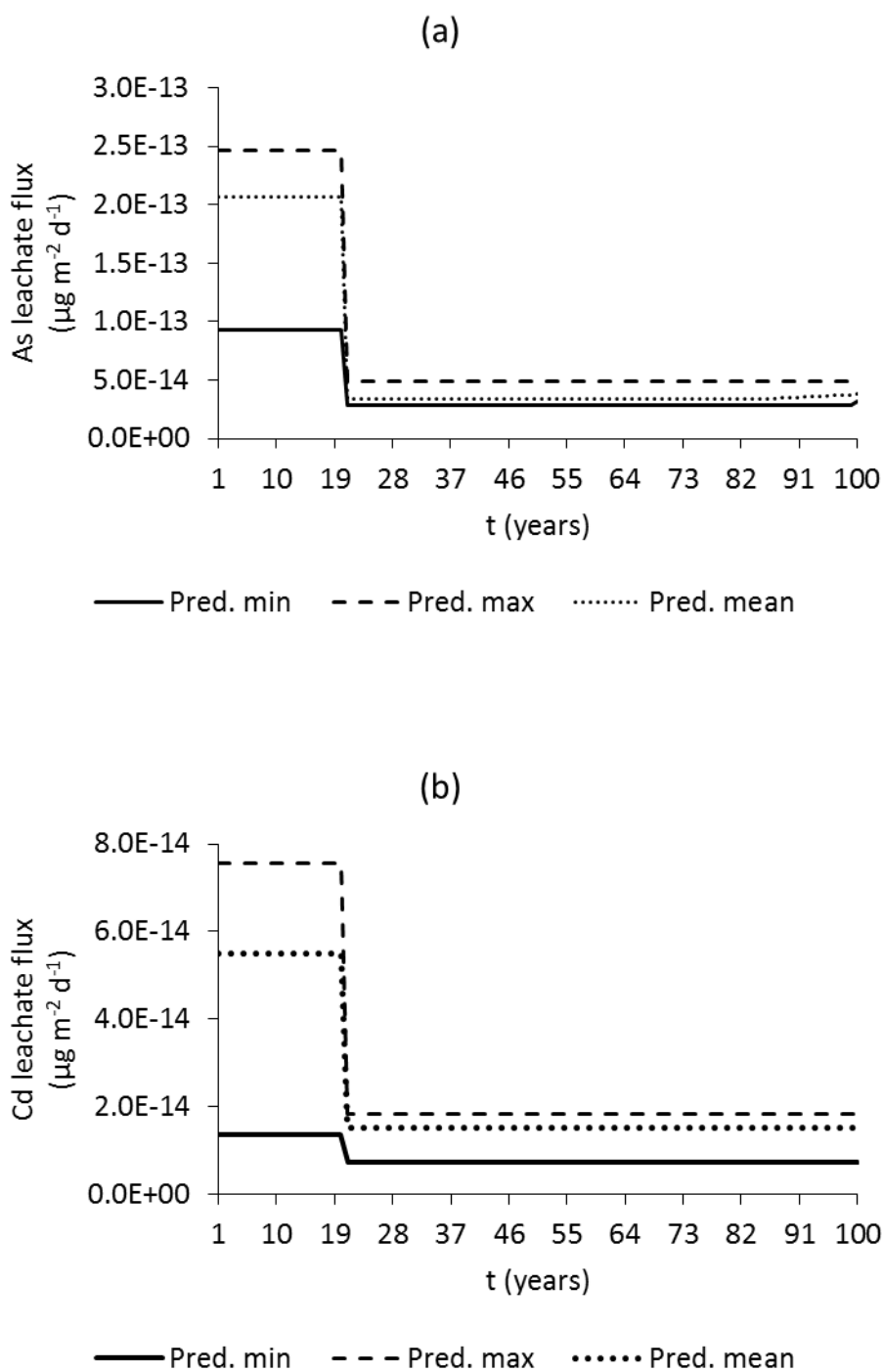


Figure 37. As and Cd concentration in the lechate. Predicted minimum, maximum and mean were estimated from 2000 Monte Carlo realizations. Leachate flux for As and Cd is averaged up to year 20 and from year 20 to year 100.

thus, confirming the existence of this mechanism. However, the role played by this mechanism in transporting metals is of minor importance if agronomic rate based applications are practiced.

Model predicts no impairment of groundwater from metals contained in land applied biosolids in this scenario. Field studies (14-year application) show metal mobility is limited and even in a low pH (5.8), coarse soil field application of biosolids, Cu and Zn did not affect groundwater (depth to water = 10.5 m) (Sukkariyah B, 2007). A 11 year field study (6 application) also reported Cd remained in the till zone (Barbarick et al., 1998). Cd movement below the till zone is reported to be negligible even at high application rates after 14 years (Dowdy et al., 1991).

The Cd load to the downstream waterbody follows the same trend as of runoff and eroded biosolids-soil particles (Figure 38) with higher runoff years yielding higher TSS. The repeating of the trends observed in Figure 38 are the outcome of repeating the 11 years of meteorological data that was processed for the area. There will be no change in the amount of annual precipitation due to changes in climate for the Yakima River basin (Vano et al., 2010), therefore repeating the precipitation data over the simulation period is a realistic scenario.

The mass balance of all the processes modeled is shown in Figure 39. At the end of 20 years of consecutive biosolids application As and Cd mostly remains in the till zone. Lower soil/biosolids – water partition coefficient for As in comparison to Cd primarily results in twice the mass lost to the buffer region. Similarly, As lost due to leaching is an order of magnitude higher than Cd at year 20, which can be attributed to the same parameter (soil/biosolids – water partition coefficient). The plant uptake fraction also reflects the coefficients specified and is approximately seven (7) times higher for Cd in comparison to As. The mass lost due to emissions and runoff from the buffer region are very small for both As and Cd. Heavy metal loss in the

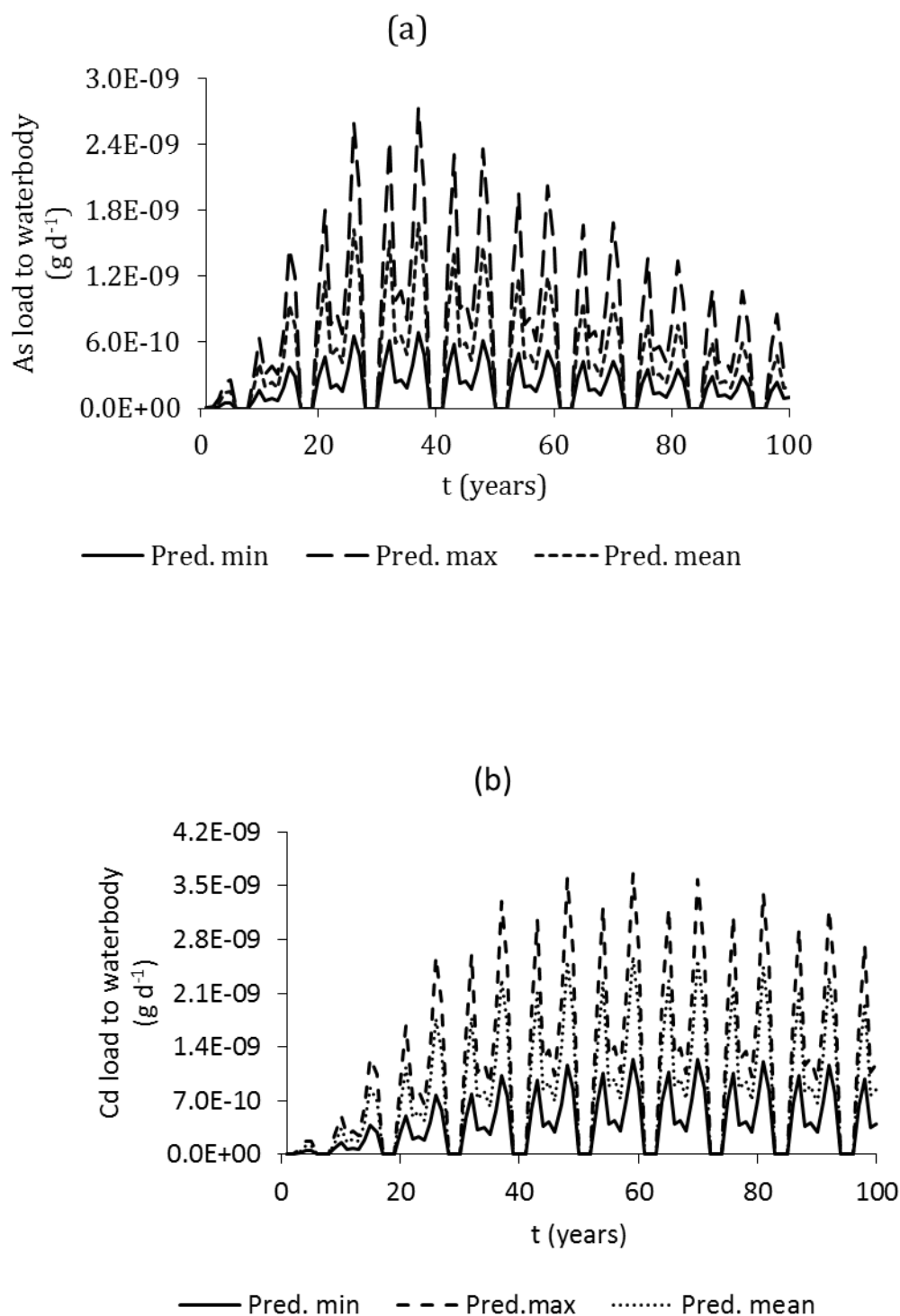


Figure 38. As and Cd load to the downstream waterbody (reach 3). Predicted minimum, maximum and mean were estimated from 2000 Monte Carlo realizations. Repeating patterns are the result of meteorological data repetition. Climate change does not have any significant impact on precipitation in Yakima Valley.

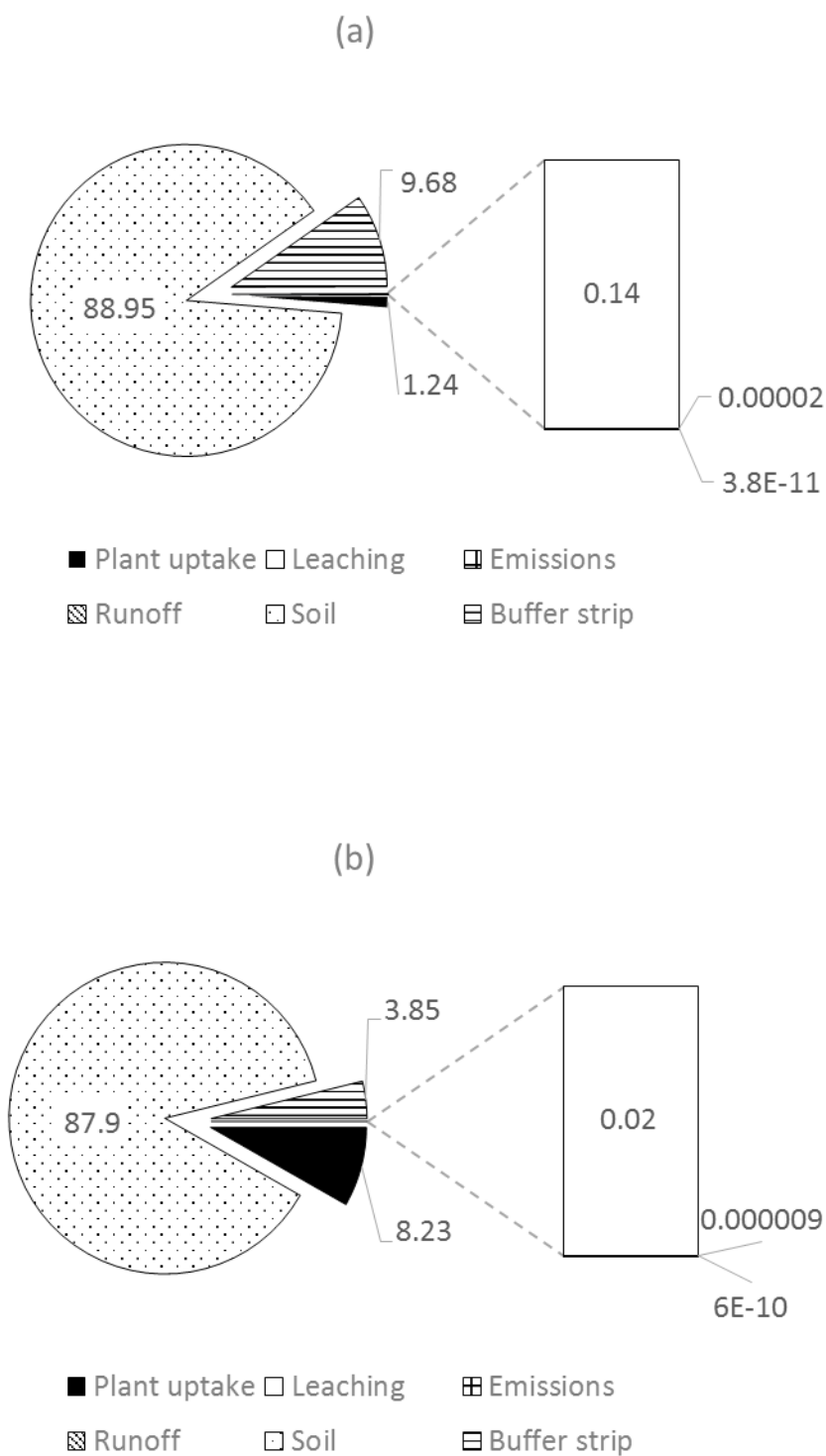


Figure 39. Mass balance of (a) As and (b) Cd at year 20 following 20 consecutive biosolids land applications at ceiling concentrations. Mass lost through Runoff and Emissions small compared to other loss mechanism and compartments. Predicted mean was estimated from 2000 Monte Carlo realizations.

runoff compartment (three years field monitoring) is low and is considered not to be a cause for concern (Joshua et al., 1998).

4.4. Cancer and Non-cancer Risk from As and Cd Solely from Biosolids

This section describes the differences in the cancer and non-cancer risk outcomes when the effects of just biosolids land application activities are considered. To accomplish this objective the calibrated and validated 3MRA model is applied to ascertain the risk and HQ to the human receptors residing in the vicinity of the site (in the AOI). Cancer and non-cancer outcomes at ceiling concentration loading rates for the regulated chemical constituents As and Cd are very low for the soil ingestion pathway (see Figure 40). As the loading rates do not contaminate the groundwater the HQ values are zero for pathways that are related to groundwater. Similarly, the risk from 20 years application scenario is below $1E-6$ risk for both As and Cd for two of the four pathways that were modeled (see Figure 41 and Figure 42). These risks are estimated based on the assumption that the peak concentration predicted during the simulation occurs during the life time of the person being exposed. However, even when using peak concentration excess risk values resulting from biosolids land application activities are very low. CSF for Cd does not exist for the soil ingestion exposure pathway and hence, was not estimated. Thus, comparing with the risk introduced from background concentration the risk solely from biosolids are well below the $1e-6$ limits and do not constitute a cause for concern through any pathway modeled here. The risk from combined exposure of inhalation as well as ingestion does not present a cause for concern.

It is well known that agricultural soils can contain high levels of heavy metals (e.g., Cu, Pb and As) introduced from pesticides and weedicides (Breslin, 1999). Thus, it is important to

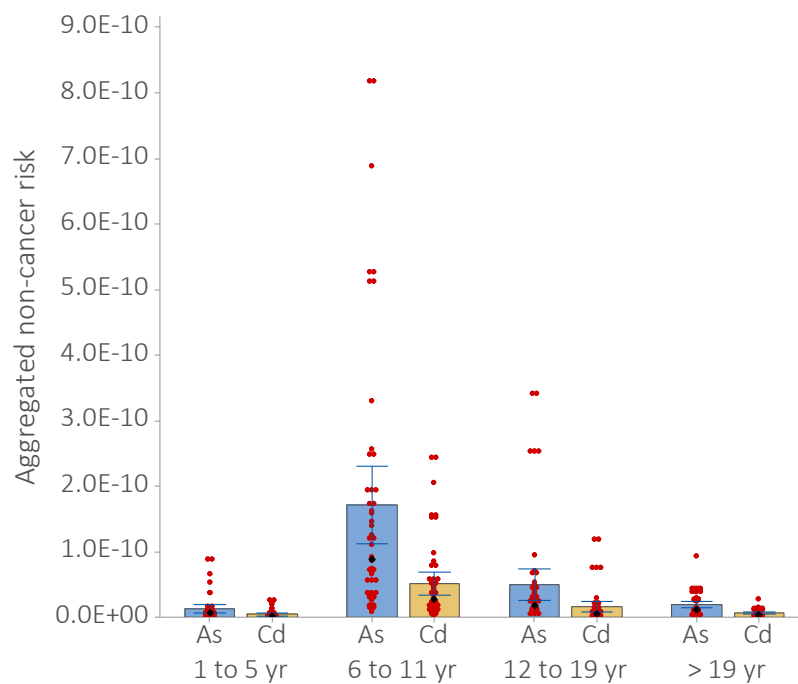


Figure 40. Hazard Quotient (HQ) estimates resulting from biosolids land application. Activities are very low in comparison to unacceptable level of 1 and is not a cause for concern. Error bars represent standard deviation and dots represent individual values.

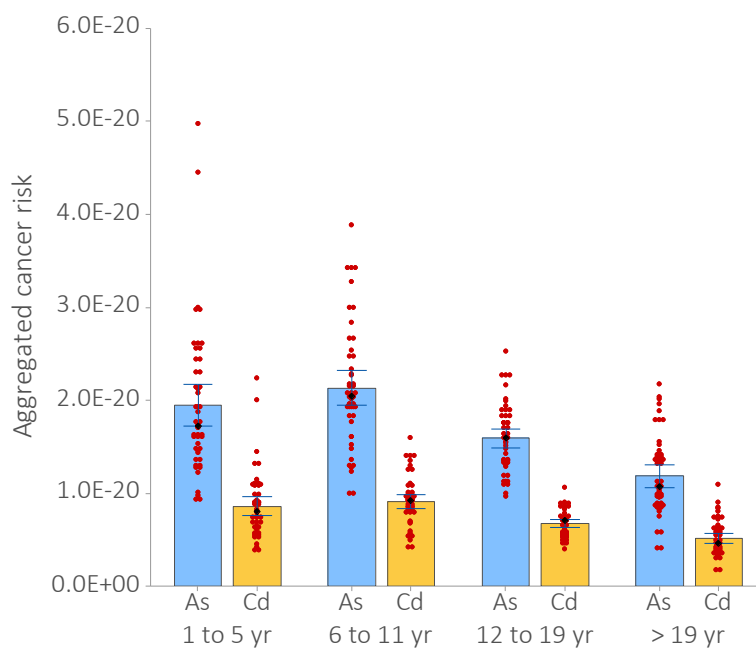


Figure 41. Cancer risk from air inhalation. This pathway also presents very low risk and is well under the $1E-6$ risk criteria. Error bars represent standard deviation and dots represent individual values.

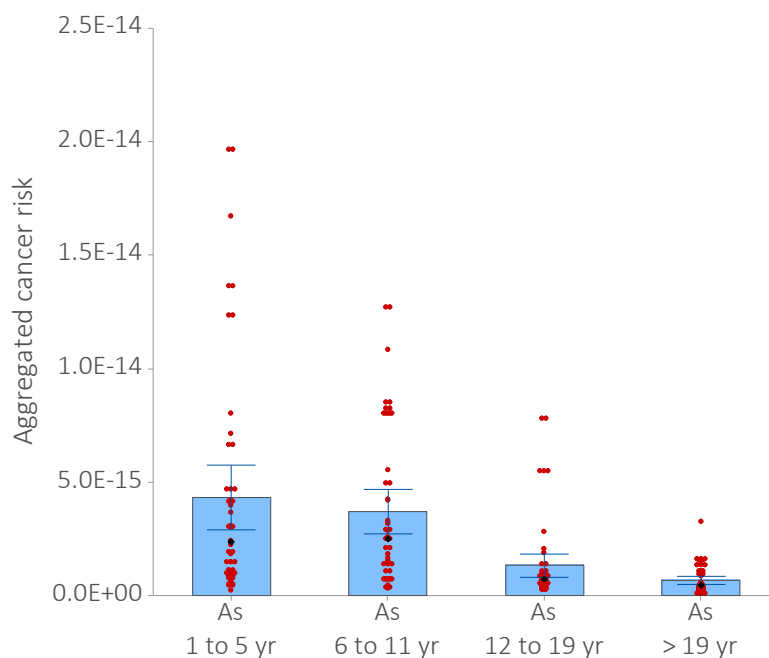


Figure 42. Cancer risk from soil ingestion. This pathway also presents very low risk and is well under the $1\text{E-}6$ risk criteria. Error bars represent standard deviation and dots represent individual values.

isolate the risk that results solely from land application activities to communicate risk to the public.

4.5. Groundwater Pathway

No realistic agricultural application scenario currently allowed within Part 503 for biosolids land application resulted at impairing groundwater at Yakima Valley biosolids land application site. Thus, several scenarios were simulated to determine the circumstances under which groundwater impairment could occur. These scenarios were evaluated by considering higher biosolids application rates, decreased depth to water tables and higher regulated metal loading rates. It is also assumed that the drinking water well is located at specified location (X,Y) usually at $X = 1000\text{m}$ and $Y = 1000\text{m}$ from the site centroid in the direction of the groundwater flow and is hydrologically connected to the biosolids land application site. In other words, the

contaminant plume generated by biosolids land application will affect the water withdrawn from the drinking water well.

The tillage depth was kept constant for all the simulations at 0.2m and the operational life of the site was fixed at 40 years. Dewatered biosolids at 40% solids content was applied to all three sites. All three of the sites were classified under bedded sedimentary rocks (US EPA, 1996a) which then allowed for assignments of hydrogeological parameters at regional level. Depth to water table specifications, number of cultivations and site area assignments were based on data gathered in the survey. Three sites were selected for assessing exposure through the groundwater pathway and includes sites from Washington, Georgia and Virginia. In addition to As and Cd, Ni, Se and Zn were also evaluated for this assessment. Hazard Quotients (HQ) or non-cancer risks were estimated considering exposure from drinking impaired groundwater (groundwater ingestion pathway). An HQ value greater than 1 may pose an unacceptable non-cancer risk. These results were generated using Biosolids and Groundwater Tool (BGRST) for the three sites and tabulated values are provided in APPENDIX C – HQ from drinking impaired groundwater (see Table C - 1 to Table C - 30).

Four application rates (4, 8, 20 and 40 tons per acre) were considered and for each application rate the concentration of the contaminant were varied from 1X to 10X times ceiling concentration (see Table C - 1 to Table C - 4, Table C - 11 to Table C - 14 and Table C - 21 to Table C - 24) for the three sites. A non-zero HQ value was only observed after reaching a certain threshold value. A summary of what minimum application rate generates a non-zero HQ and the maximum HQ predicted is listed in Table 18. None of these values reach the HQ value of one and therefore does not constitute a health concern. As and Se are more of a concern as they resulted in a nonzero HQ value at the lowest application rate scenario simulated (4 tons per acre).

Table 18. Summary of minimum application rates and maximum HQ for the 4, 8, 20 and 40 tons per acre and 1X, 2X, 5X and 10X times the ceiling concentration

Regulated pollutants	As	Cd	Ni	Se	Zn
VA					
Minimum application rate resulting in non-zero HQ (tons/acre)	8	>40	40	4	40
Highest HQ predicted	5.1e-5	NMRW	2.71e-8	6.63e-3	6.53e-10
WA					
Minimum application rate resulting in non-zero HQ (tons/acre)	4	40	20	4	20
Highest HQ predicted	1.06e-5	3.03e-7	1.47e-6	4.74e-5	1.44e-8
GA					
Minimum application rate resulting in non-zero HQ (tons/acre)	4	40	20	4	20
Highest HQ predicted	3.98e-5	1.79e-9	1.78e-6	3.03e-3	3.39e-8

Site based variability in depth to water and its implication on biosolids land application is explored. In general, at 10m depth to water, none of the three sites evaluated resulted in a non-zero HQ outcome. Even at 0.5m depth to water the HQ values for high metal loading rates (10X) did not result in HQ>1. Other than the site at Georgia, only Se and As resulted in a non-zero HQ value. At Georgia non-zero HQ value was predicted for Ni at 0.5m depth to water. From a groundwater management perspective, primarily As and Se may be a cause for concern and at some other sites Ni may be an issue as well. In terms of vulnerability of site from a particular chemical constituent, Se is the most mobile followed by As. Ni, Cd and Zn are less mobile. Similar behavior were observed by other several researchers (Biddappa et al., 1981; Harter and Lehmann, 1983; Toribio and Romanyà, 2006).

Figure 43 shows variability in the vulnerability of different sites towards different regulated constituents. For example, the site located in the state of Virginia exhibits higher vulnerability towards As and Se. On the other hand, the site in Washington State is more vulnerable to Cd and Zn. The site located in the state of Georgia is vulnerable to Ni. These results indicate that variability between sites could result in increased hazard quotient for one chemical

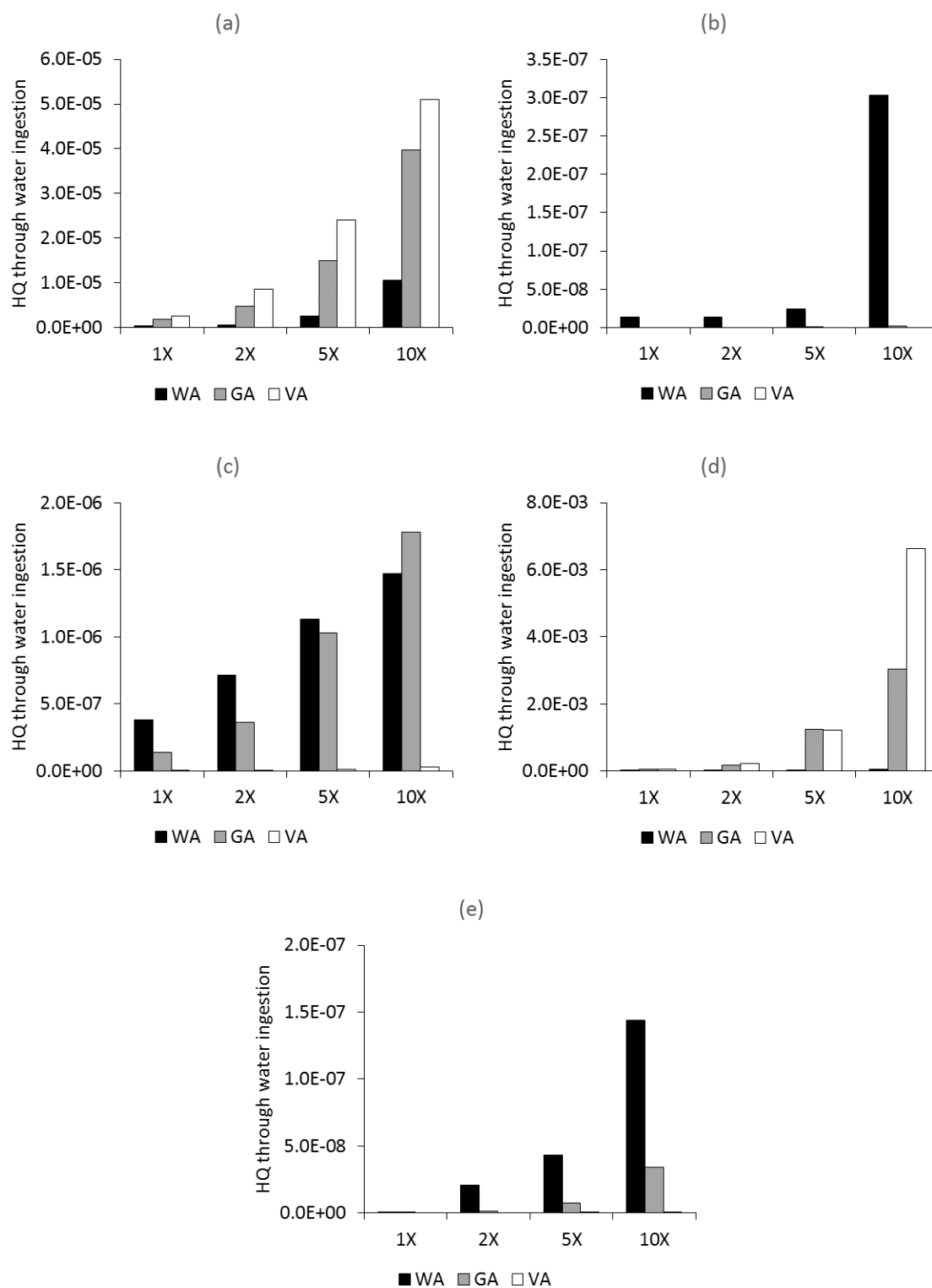


Figure 43. Variability in the vulnerability of sites to different regulated pollutants for 40 tons per acre biosolids application rate: (a) As, (b) Cd, (c) Ni, (d) Se and (e) Zn.

constituent even though the same biosolids are being land applied at all locations. Thus, the toxicity characteristics of a particular biosolids is a function of where it is being land applied rather than the biosolids itself. However, it should be noted that even at 40 tons per acre and 10X ceiling concentration heavy metal loading rates, the HQ values resulting from drinking impaired groundwater is well below 1.

Another scenario was evaluated to determine the impact of biosolids storage sites which can contain large quantities of biosolids, such as biosolids holding facilities prior to land application. A very high loading rate of 200 and 400 tons per acre were evaluated. This scenario results in $HQ > 1$ at 50 and 200m from the site even for 1X concentration for As, Ni and Se. For Cd a $HQ > 1$ was predicted for 2X and 10X for Zn.

4.6. Importance of Buffer Strip

The region between the site and the downstream water body (buffer strip) receives contaminant loadings from the site due to runoff and aerial deposition. Hence, the contamination of the soil layers occurs from top layer to the bottom layer (e.g., Figure 34). The buffer strip continues to increase in As and Cd concentration even after application activities have completely ceased. However, the depth averaged concentration in the buffer strip is approximately 3 orders of magnitude lower than the site for both As and Cd (see Figure 44). There is delay in the occurrence of the peak for the buffer strip (around 30 years) for both As and Cd. The implications of this behavior is, even though a land applier terminates application, the site continues to affect the surrounding areas.

4.7. Evaluation of Non-regulated Emerging Chemical Constituents: B(a)P and DEHP

Biosolids land application with two organic chemical constituents (B(a)P and DEHP) was simulated for consecutive annual applications for a period of 100 years at an agronomic

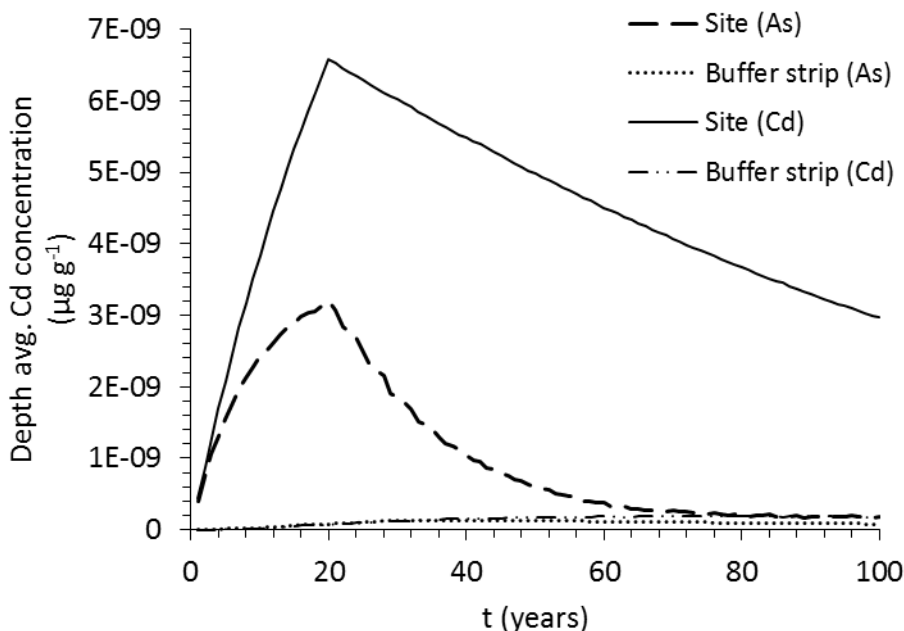


Figure 44. Continued effect of land application on the buffer strip (a) As and (b) Cd.

application rate of $1.481 \times 10^{-3} \text{ Mg/m}^2$ and a solids content of 20%. The concentration of B(a)P and DEHP considered for this assessment are 5.02 and 162 mg/kg DW basis and was gathered from the biosolids annual report (King County, 1995; King County, 1996; King County, 1997; King County, 1998; King County, 1999).

The concentration of B(a)P and DEHP continues to rise in the till zone until they reach a steady state (see Figure 45). B(a)P reaches a steady state concentration of $1.3 \times 10^{-10} \text{ µg/g}$ and DEHP a concentration of $1.1 \times 10^{-9} \text{ µg/g}$ although both were applied at very different initial concentrations. There are 2 orders of magnitude difference between the two chemicals during application; however, at the end of the 20-year period, there is only an order of a magnitude difference in concentration between the two contaminants. B(a)P reaches its steady state concentration at around year 20, whereas DEHP at around year 4. Both contaminants remain at their steady state concentrations for the rest of the simulation even

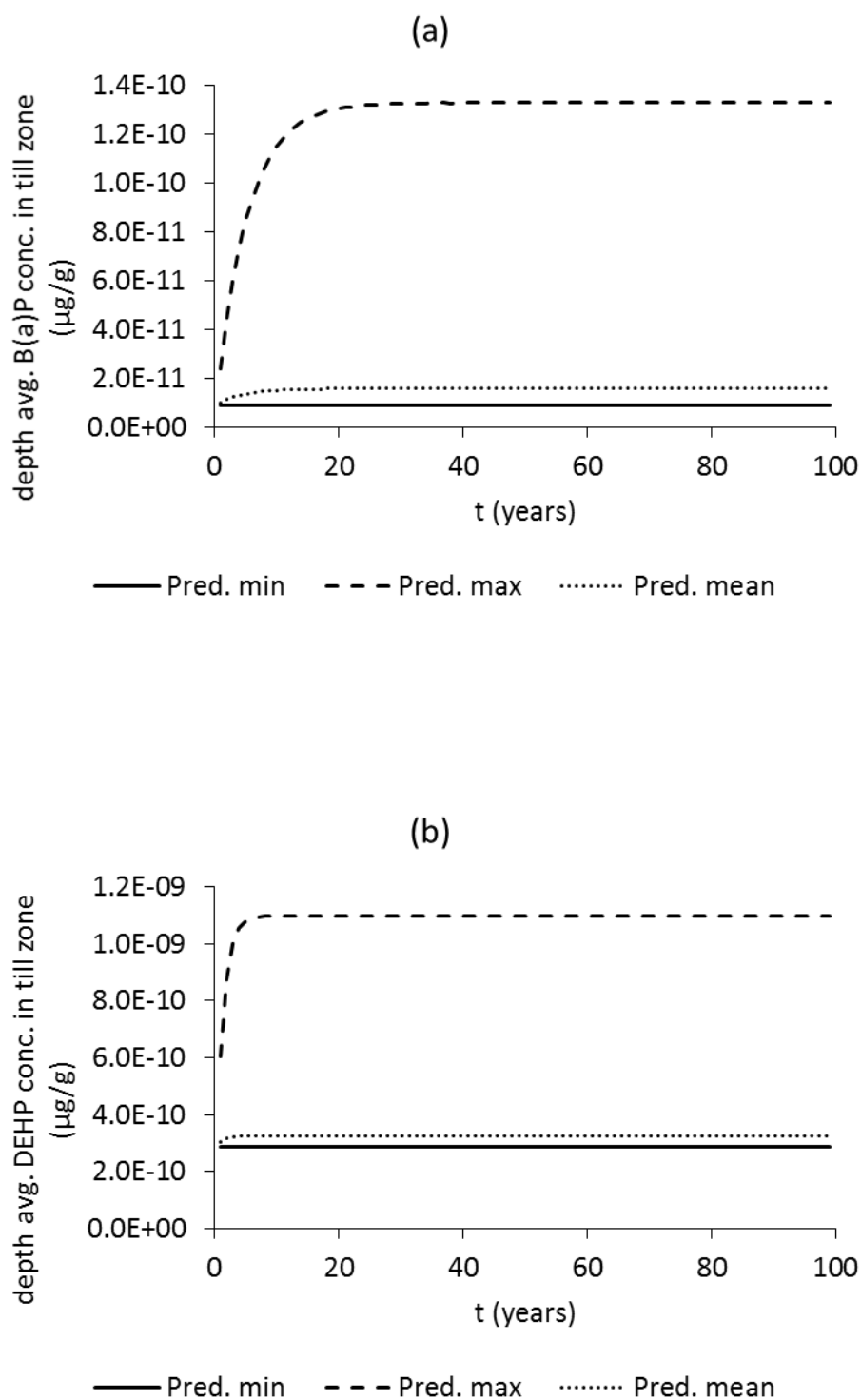


Figure 45. Annually averaged depth averaged contaminant concentration in the till zone (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

though annual biosolids additions continue to occur. The steady state observation is also reported in the technical background document of Part 503 for B(a)P (US EPA, 1992b).

The contaminant mass associated with PM30 emissions exhibits the same trend as contaminant concentration in the till zone. This is expected as the concentration in the soil flattens with time and the mass associated with particulate emissions will also reflect the same pattern as the soil concentration. Similar to the soil concentrations B(a)P reaches steady state later than DEHP (see Figure 46). There is not much difference between the two constituent mass associates with the PM30 emissions during the steady phase.

B(a)P volatilization also exhibits the same trend as depth averaged concentration and eventually reaching a steady state (see Figure 47). However, the loss of the contaminant through this pathway does not constitute is insignificant similar to the observations made by other authors (Wilson and Jones, 1993). The concentration of B(a)P is approximately an order of magnitude lower than DEHP in the buffer strip (see Figure 48). Similar to the till zone the concentration in the buffer strip does not increase with continuous application and reaches a steady state. The concentration in the surficial layer also exhibits similar behavior where continuous additions of biosolids does not result in increases in concentration. The concentration reaches a steady state (see Figure 49). Both B(a)P and DEHP mass exiting the bottom boundary of the till zone are constant for the entire simulation (see Figure 50). The B(a)P and DEHP load to the waterbody increases and reaches a steady state as well (see Figure 51).

In order to contrast with regulated metals simulation, the mass balance at the end of year 20 is shown in Figure 52 (a) and (b). Nearly all of the contaminant mass introduced to the till zone from land applied biosolids are aerobically degraded. During the 20 years of consecutive application 15.64 kg of B(a)P is added to the till zone of which 96.76% decays. The decay of B(a)P

within the model was accomplished through aerobic biodegradation as abiotic processes are reported to be significant only up to four or fewer aromatic rings (Wild and Jones, 1993; Álvarez-Bernal et al., 2006). With manure additions to B(a)P spiked soils, studies have shown 74% removal within the first 100 days (Álvarez-Bernal et al., 2006).

Similarly, of the 505 kg of DEHP added to the till zone 97.94% decays. Also, 3.20% of B(a)P and 2.05% of DEHP remains in the till zone after 20 years. The combined losses to other compartments are less than 0.04% for B(a)P and $4.33 \times 10^{-3}\%$ for DEHP. In a three year field study DEHP at the end of each year was between 5-6% of the concentration that was applied (Petersen et al., 2003). Fifty percent degradation of initially applied DEHP was observed in a 30 day study (Xu et al., 2008). It is reported that DEHP degradation occurs primarily through aerobic biodegrading process (Petersen et al., 2003; Xu et al., 2008).

The only pathway that resulted in a non-zero cancer risk estimate is the soil ingestion pathway. However, for both B(a)P and DEHP the risk from this pathway is very low and well below the unacceptable risk criteria $1E-6$ (see Figure 53). Thus, the presence of these two constituents in biosolids is not a cause for concern based on this modeling effort for this site at the loading rates and application rates simulated.

Plant uptake of DEHP is reported; however, no relationship has been established between concentration of DEHP in soil (introduced from biosolids or other wastes) and concentration of DEHP in plant (Petersen et al., 2003). Limited uptake of DEHP by plants is reported by several studies; however, even such uptake is questioned as the measurements in plants total ^{14}C (Aranda et al., 1989; Stales et al., 1997). B(a)P is primarily removed from soil by microbial activity (Rivera-Espinoza and Dendooven, 2007). The applicability of using plant uptake coefficients using linearized uptake function is also ambiguous (Samsøe-Petersen et al., 2002). The PAH, B(a)P and the phthalate ester di-(2-ethylhexyl) phthalate (DEHP) both mostly

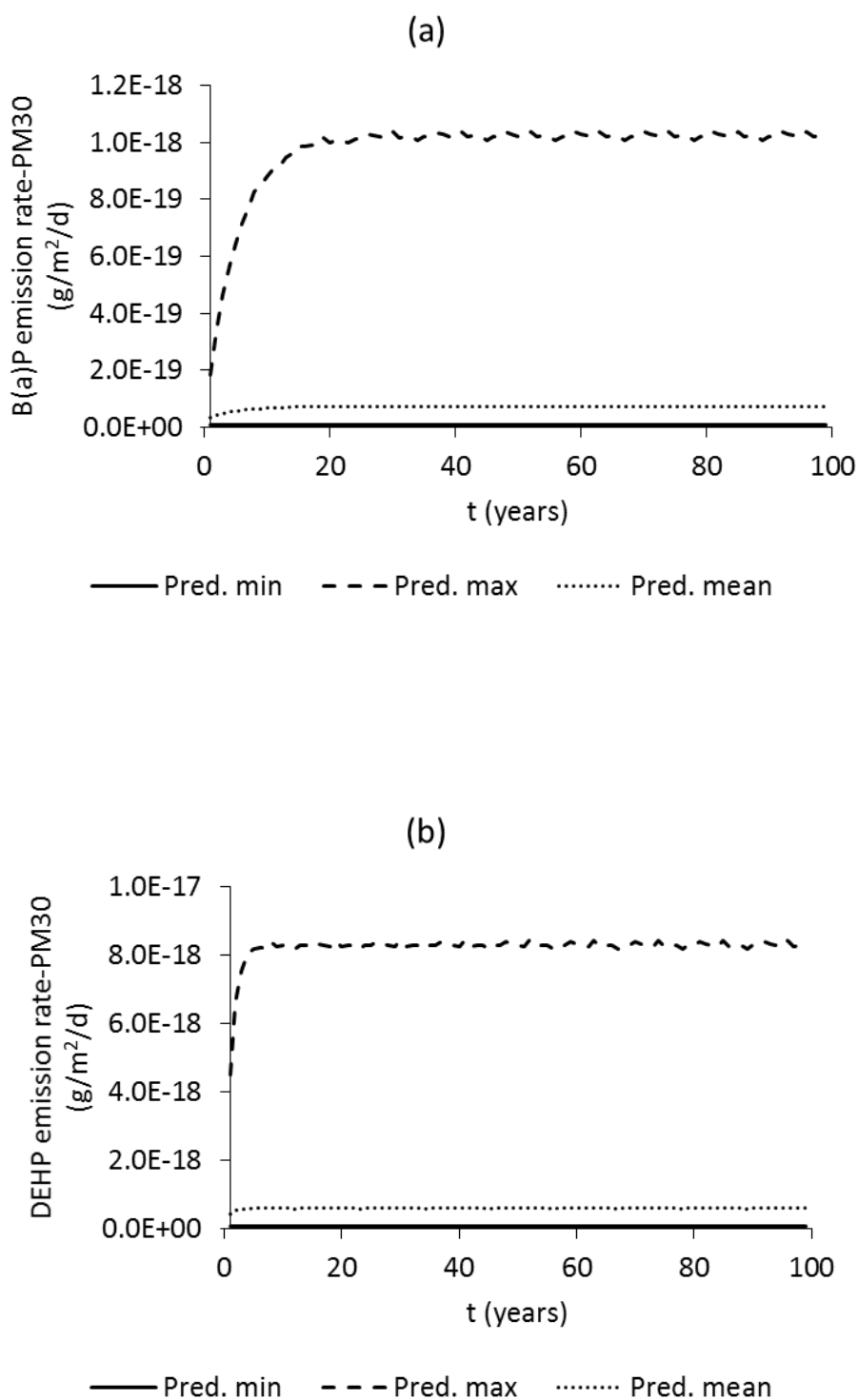


Figure 46. Contaminant mass emission rate from the site during the 100 years of simulation (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

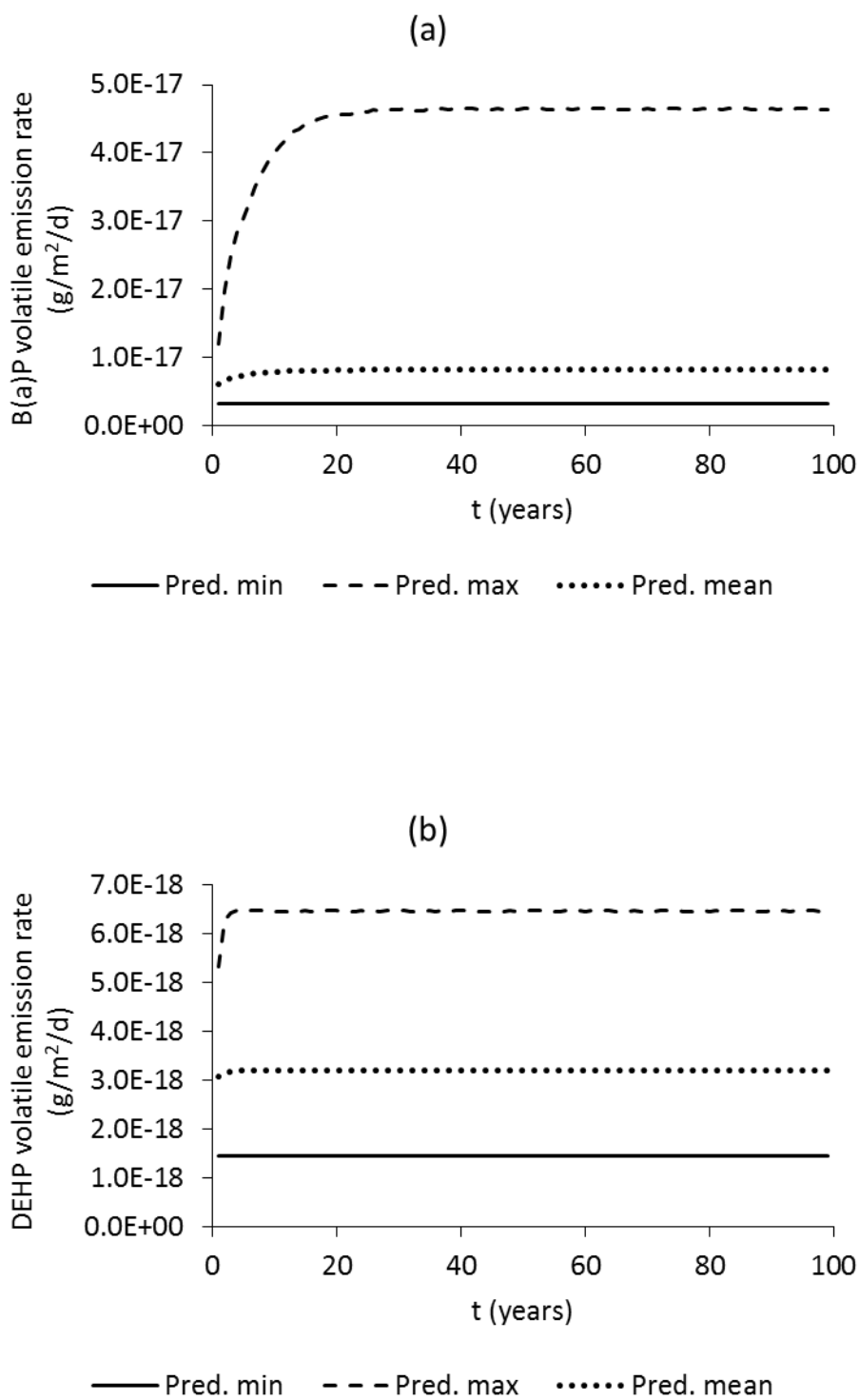


Figure 47. Contaminant mass lost due to volatilization of (a) B(a)P and (b)DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

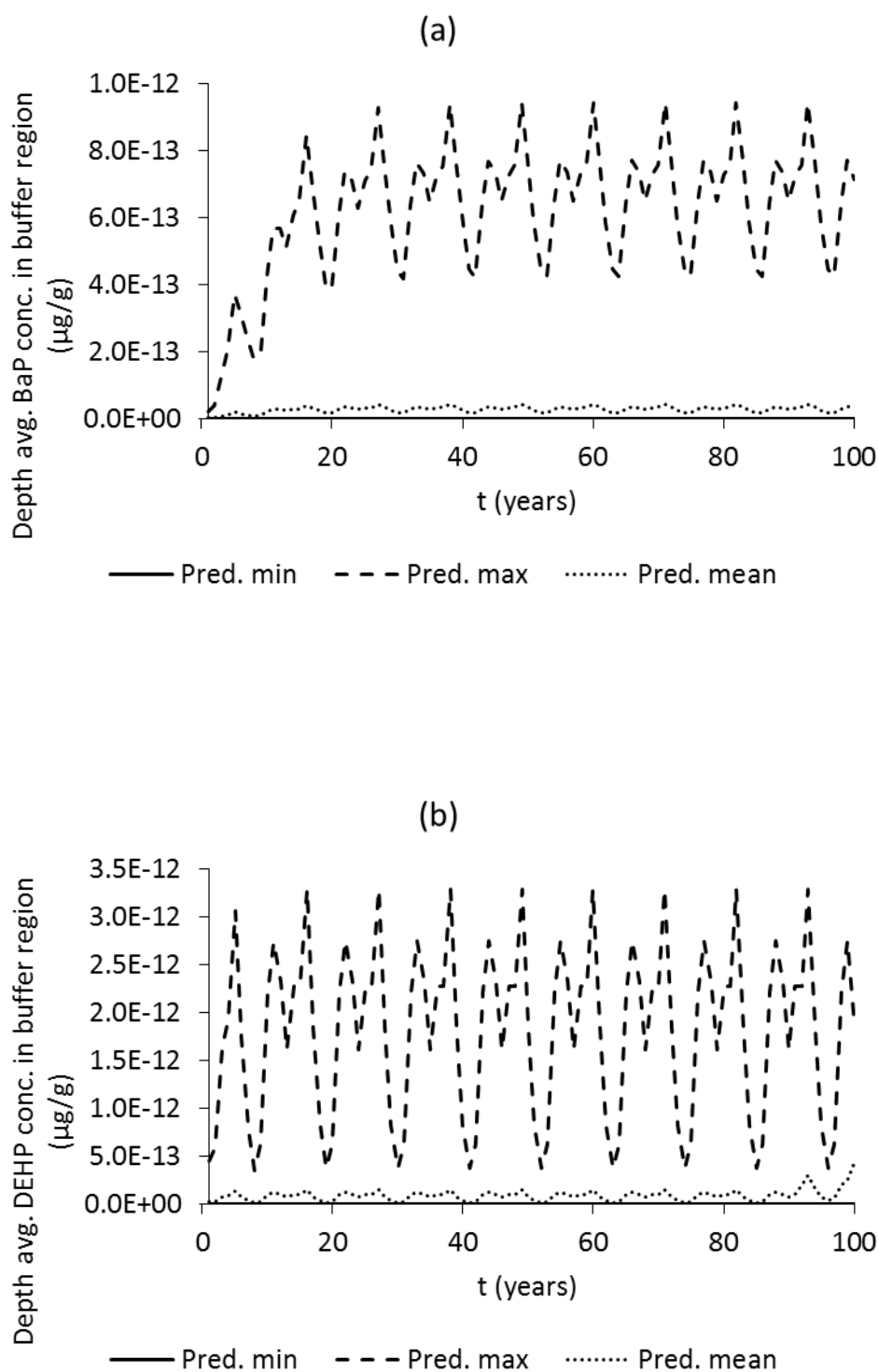


Figure 48. Annually averaged depth averaged contaminant concentration in the buffer strip (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

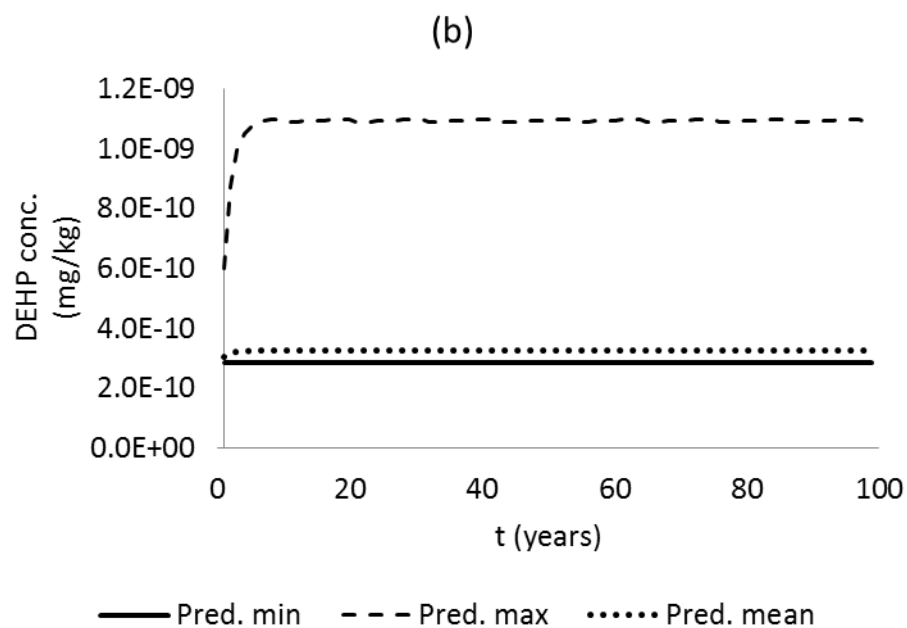
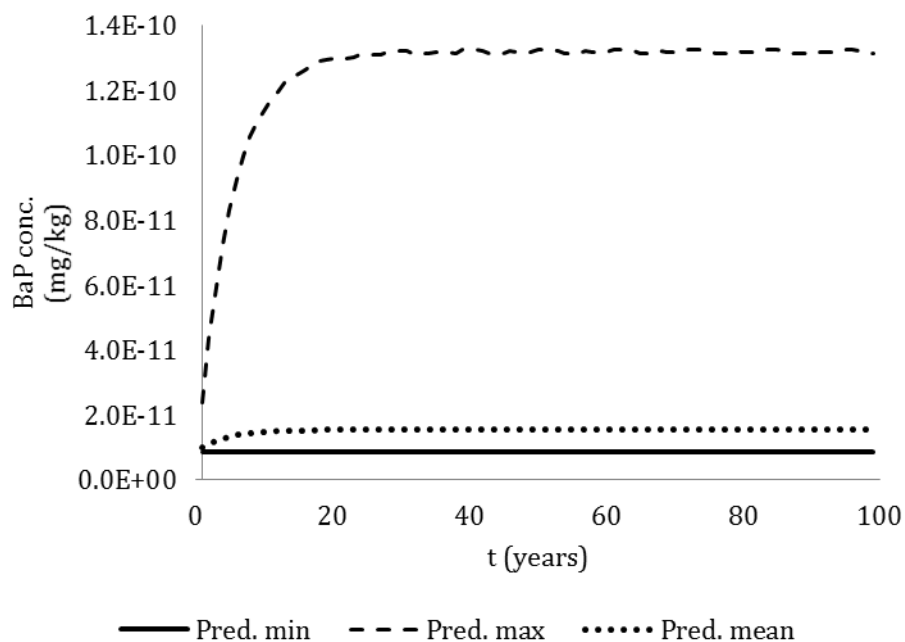


Figure 49. Surface soil contaminant concentration (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

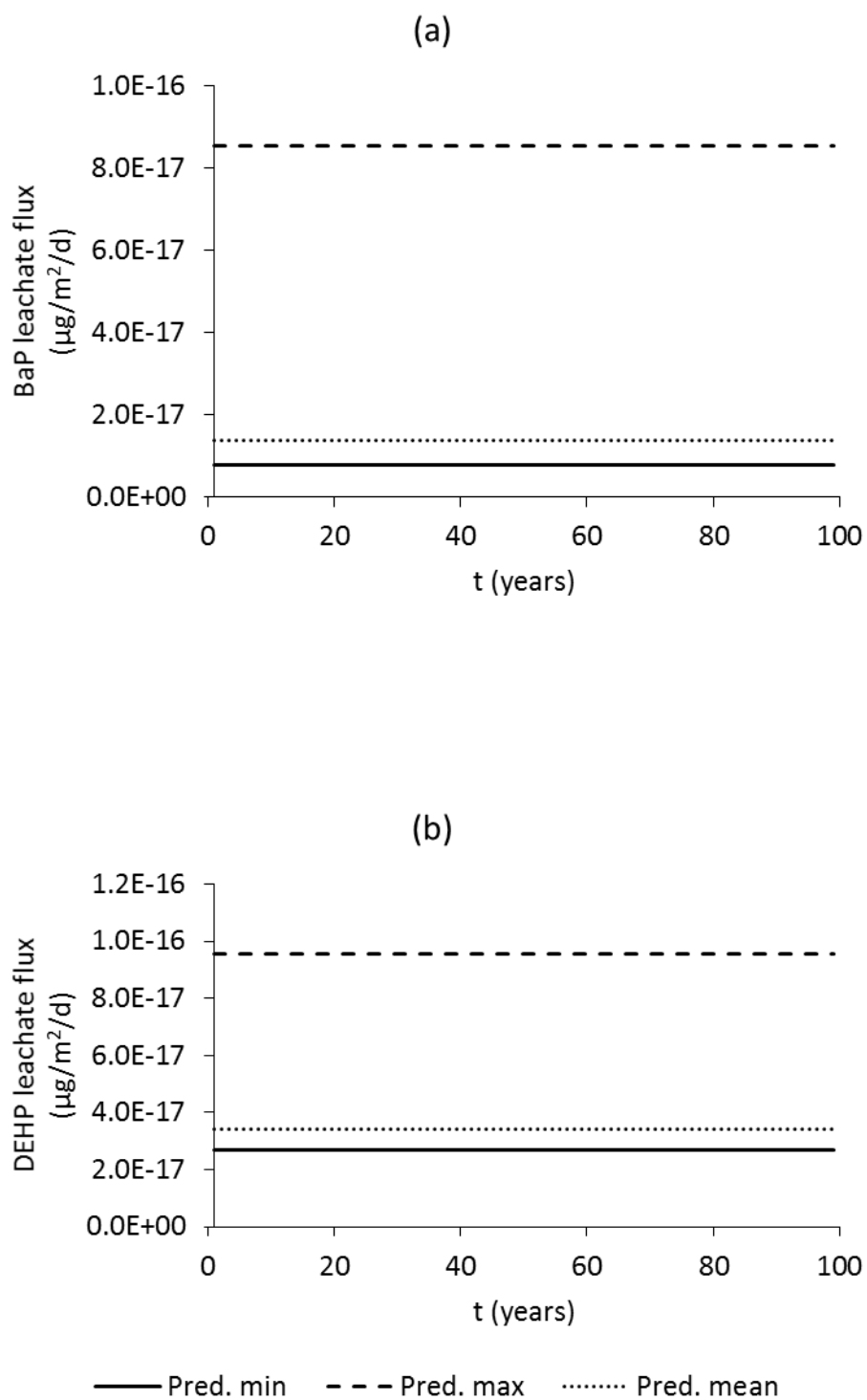


Figure 50. Contaminant concentration in the leachate for (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are calculated from 2000 Monte Carlo realizations.

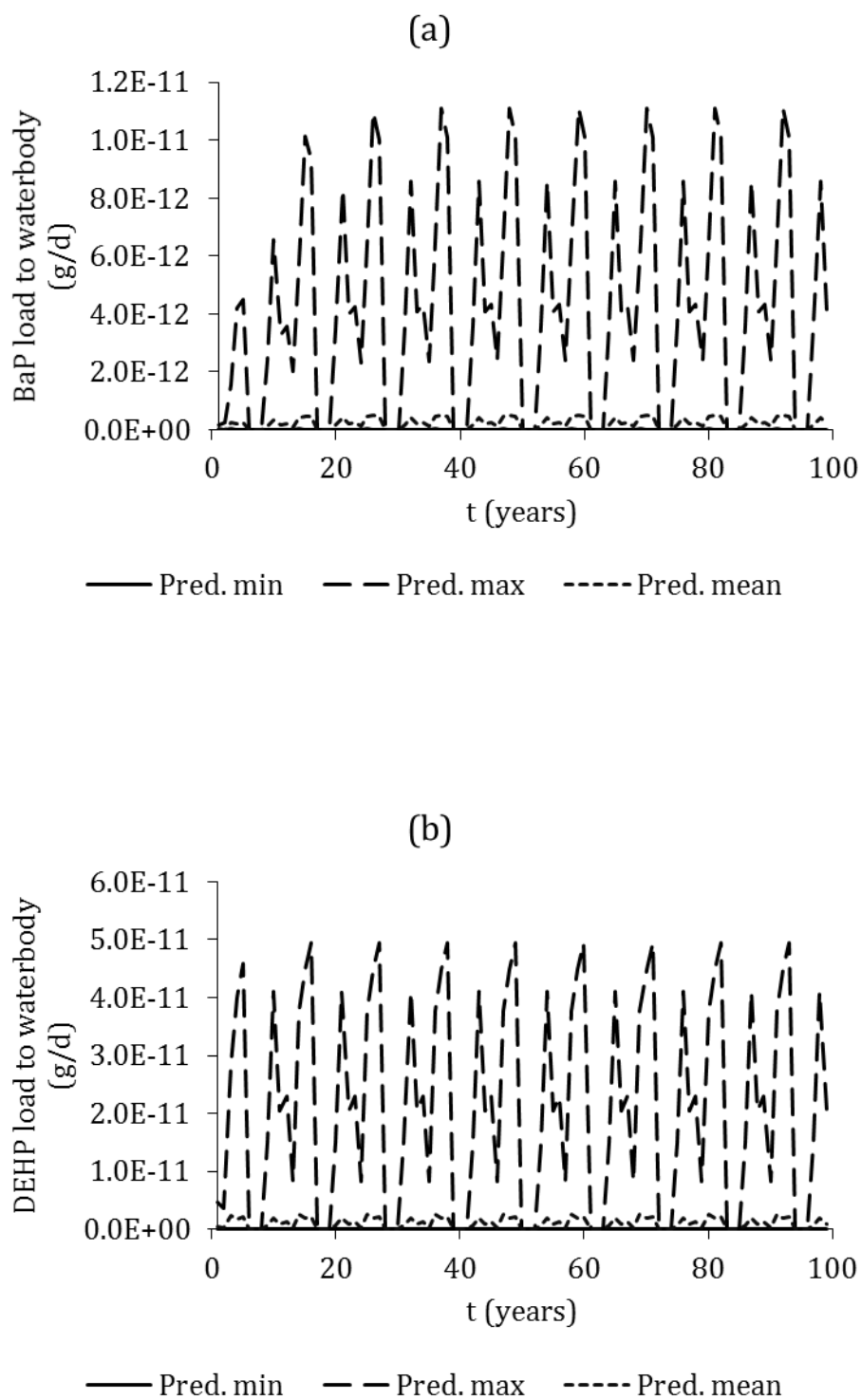


Figure 51. Contaminant load to the water body (a) B(a)P and (b) DEHP. The predicted maximum, minimum and averages are the outcome of 2000 Monte Carlo realizations.

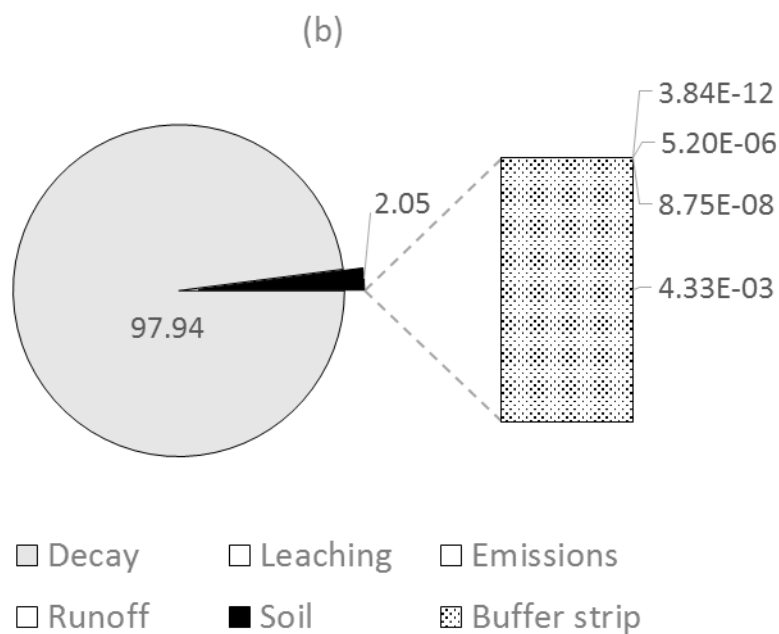
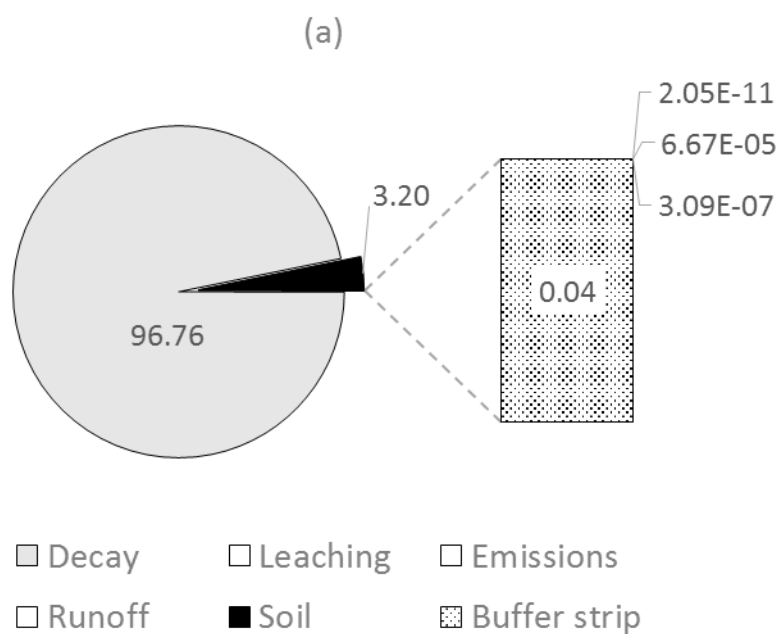


Figure 52. Mass balance of B(a)P and (b) DEHP at year 20 following termination of land application. The values representing each of the compartments are averages from the 2000 Monte Carlo realizations.

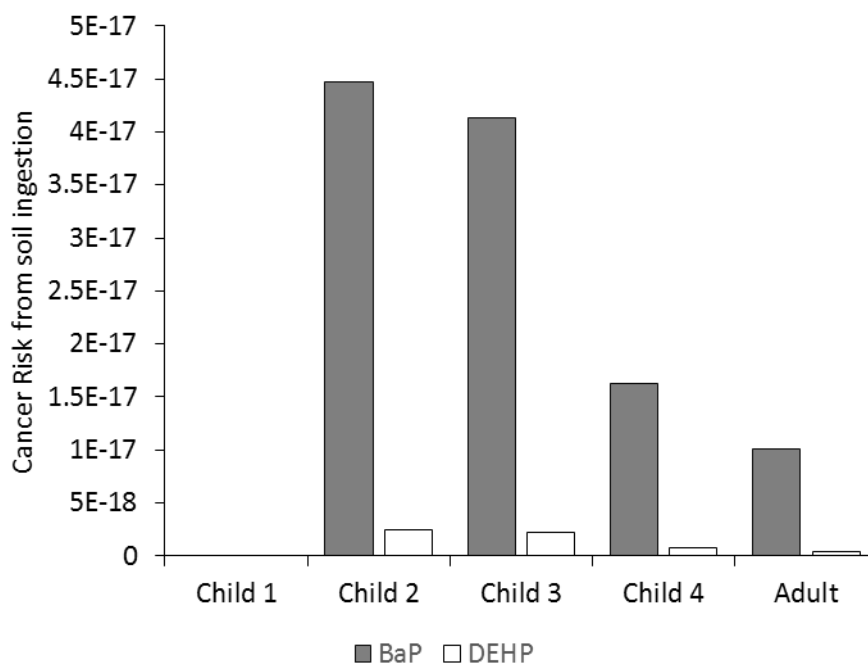


Figure 53. Cancer risk from ingesting soil contaminated with B(a)P and DEHP.

degrades based on model predictions. Consequently the risk from all the 13 pathways evaluated presents no additional unacceptable risk from the practice.

4.8. Comparison of Biosolids Chemical Concentration with Food Sources

The reluctance in the acceptance of biosolids as a soil amendment stems from several factors, such as the “yuck factor” – relating to its origin, unknown long-term negative effects and odor among several others (Beecher et al., 2004). Several of these perceived factors (Innate or learned aversions) are understandable as human beings are instinctively averse to fecal material and its derived products (such as biosolids) (Petrof and Khoruts, 2014). In addition to this instinctual aversion to fecal material products, odors are critical to the acceptance by the public (McGinley and McGinley, 2002; Beecher et al., 2004). Unpleasant odors are perceived by many in the public as high health risk whether or not there is an actual risk (Schiffman and Williams,

2005). Although factors such as the “yuck factor” are not be addressed in this study, other factors such as unknown long term negative effects or “having delayed effects” are addressed for four chemical constituents present in biosolids.

In this study, although the highest permissible concentration of the As and Cd was used to determine the risk, the land application practice did not represent any unacceptable cancer or non-cancer risk for all four chemical constituents. This was observed even when biosolids were applied consecutively for 20 years for inorganics and 100 years for organic chemical constituents. In contrast, at the study site in Yakima, there already exists health risks due to the presence of As and Cd in their soil. For example, As and Cd concentration in Yakima valley was much higher than what was being introduced through biosolids application and biosolids introduction only represents <0.0001% of the pre biosolids application soil concentration. This background concentration for As and Cd (from diverse sources, e.g., geogenic, pesticides applications and chemical fertilizer applications etc.) actually resulted in increased unacceptable cancer and non-cancer risk for the soil ingestion pathway.

In order to provide perspective for the four chemical constituents that were evaluated the concentration in biosolids are contrasted with food sources. As can be seen in Figure 54, potential human exposures to these chemical constituents can occur from various routes of exposure and in some cases at concentrations higher than that found in biosolids (see APPENDIX E – As, Cd, B(a)P and DEHP concentration in food). Therefore, it is critical to provide perspective to the public about how biosolids compare with other sources of exposure. Finally, it is recommended that the methodology used in this study should be applied to other sites and other contaminants in diverse geographic locations to answer critical questions of the public.

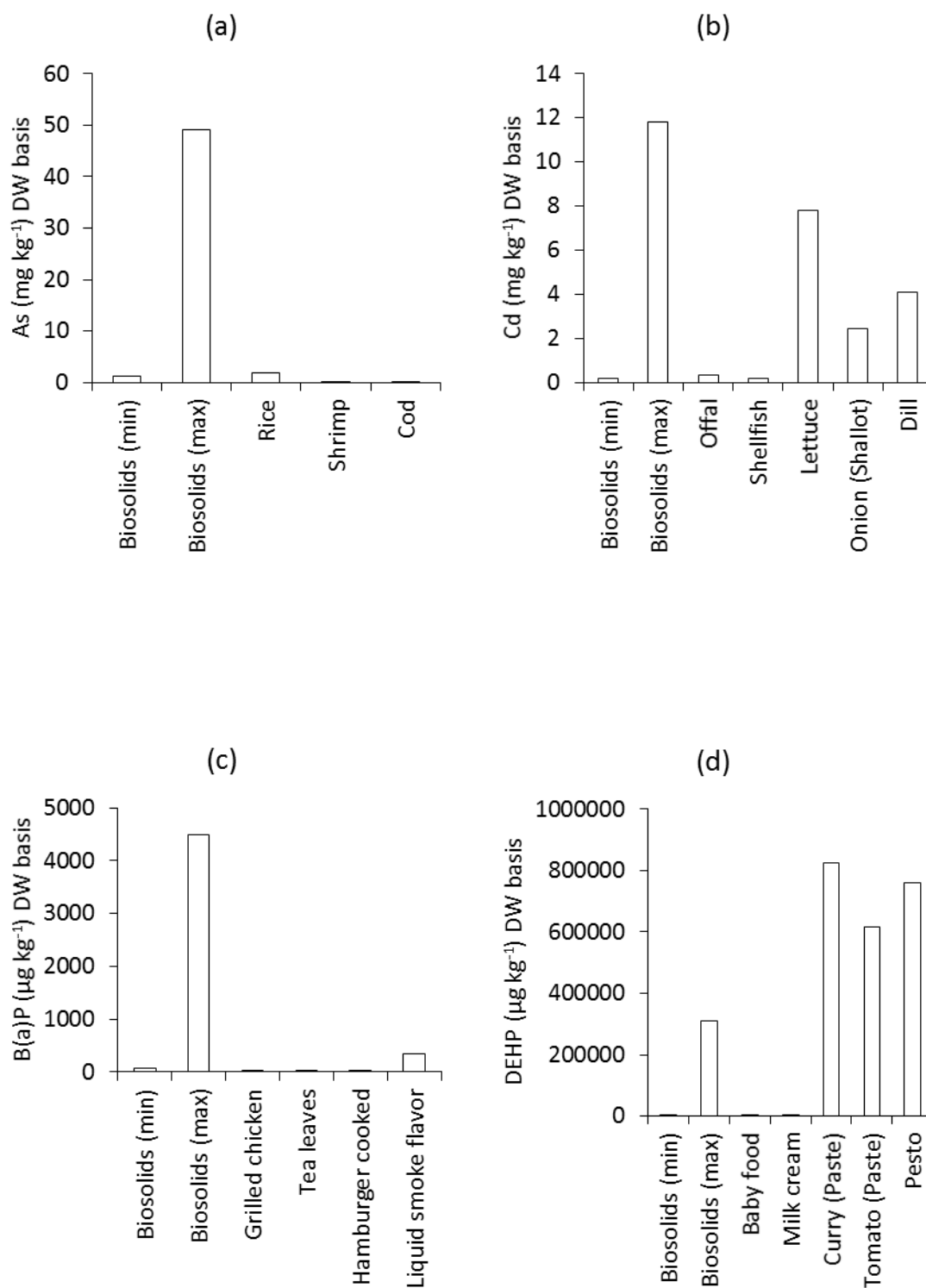


Figure 54. Comparison of (a) As, (b) Cd, (c) B(a)P and (d) DEHP concentration in food sources to biosolids concentration from TNSSS survey.

4.9. Implications

Currently the questions raised by the public are answered by land appliers simply as a practice that is allowed within the framework of the law. Historically, such answers have not satisfied the general public as evidenced by many in the community being reluctant to accept land application. Merely following a law does not answer questions about the adverse impact of biosolids. Therefore, there is need for quantitatively providing answers at the site level. This work aids as an effective communication tool between land appliers and the public.

Furthermore, it can aid in resource allocation and management. For example, questions about how long a buffer strip needs to be maintained can be answered using this model. Additionally, the following questions can be answered using the procedure provided in this work. (1) If the land has to be restored to contaminant levels that represent the pre-biosolids application period, what fraction of plant biomass should not be recycled at the site? (2) How long should buffer strips be maintained after biosolids applications are terminated?

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATION

- This modeling effort quantifies loss of seven contaminants to four pathways in a multimedia setting that are currently a cause for concern and help decision makers allocate resources and manage the practice in a scientifically sound manner at the site level.
- This modeling effort address a crucial need and implements the 3MRA framework's LAU module to quantify the sinks and losses to different compartments (e.g., soil, surface water and plant).
- In this modeling framework, the losses occurring due to simultaneous occurrences of processes that are integral to the biosolids land application practice are captured using Monte Carlo realizations.
- The benefits of land application of biosolids clearly outweigh any potential risk associated with the practice based on this modeling effort.
- This effort documents that the practice of land application is safe while considering individual chemical constituents present in biosolids even in a multipathway exposure setting.

It is important to note that the estimated risk is the result of both the background concentration and the biosolids land application practice. The cumulative risk resulting from simultaneous exposure from other pathways such as inhalation from automobile exhaust or inhalation of air contaminated (e.g. for sites located in the downstream of a coal based power plant) could all result in a much higher estimate of the potential risk. Furthermore, if site specific data is available about the duration a person has lived at a site and their drinking habits one

could estimate the actual exposure durations for carcinogens from the US EPA national value for 9 years. The human mobility data that could be obtained from cell phone records or online activity could all lead to better estimate of actual exposure. Another crucial but almost impossible effect to quantify is the synergistic and antagonistic effects resulting from exposure of multiple chemical constituents. Age difference based exposure concentration are difficult to estimate and are not considered here. Such data could further reduce the uncertainty in the estimates. This modeling effort address a crucial need and implements the 3MRA framework's LAU module to quantify the sinks and losses to different compartments (e.g., soil, surface water and plant). In this modeling framework, the losses occurring due to simultaneous occurrences of processes that are integral to the biosolids land application practice are captured using Monte Carlo realizations.

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APPENDICES

APPENDIX A – Data Processing

Table A - 1. Link between Summary Tape Files 1 from 1990 census and Summary Files 1 of 2000 census

Summary Tape Files 1			Summary Files 1
Item Code	Item Description	Data dictionary reference name	Field name
BL0010001	total persons	Universe: Total population (Total)	P001001
BL0020001	total families	Universe: Families (Total)	P031001
BL0030001	total households	Universe: Households (Total)	P015001
BL0040001	inside urbanized area	Inside urbanized areas	P002003
BL0040002	outside urbanized area	Inside urban clusters	P002004
BL0040003	rural	Rural	P002005
BL0110001	persons younger than 1 yr	Under 1 year	P014003+P014024
BL0110002	persons 1 and 2 yr	1 year+2 years	P014004+P014025+P014005+P014026
BL0110003	persons 3 and 4 yr	3 years+4 years	P014006+P014027+P014007+P014028
BL0110004	persons 5 yr	5 years	P014008+P014029
BL0110005	persons 6 yr	6 years	P014009+P014030
BL0110006	persons 7 to 9 yr	7 years+8 years+9 years	P014010+P014031+P014012+P014033+P014011+P014032
BL0110007	persons 10 and 11 yr	10 years+11 years	P014013+P014034+P014014+P014035
BL0110008	persons 12 and 13 yr	12 years+13 years	P014015+P014036+P014016+P014037
BL0110009	persons 14 yr	14 years	P014017+P014038
BL0110010	persons 15 yr	15 years	P014018+P014039
BL0110011	persons 16 yr	16 years	P014019+P014040
BL0110012	persons 17 yr	17 years	P014020+P014041
BL0110013	persons 18 yr	18 years	P014021+P014042
BL0110014	persons 19 yr	19 years	P014022+P014043
BL0110015	persons 20 yr	20 years	P012008+P012032
BL0110016	persons 21 yr	21 years	P012009+P012033
BL0110017	persons 22 to 24 yr	22 to 24 years	P012010+P012034
BL0110018	persons 25 to 29 yr	25 to 29 years	P012011+P012035
BL0110019	persons 30 to 34 yr	30 to 34 years	P012012+P012036

BL0110020	persons 35 to 39 yr	35 to 39 years	P012013+P012037
BL0110021	persons 40 to 44 yr	40 to 44 years	P012014+P012038
BL0110022	persons 45 to 49 yr	45 to 49 years	P012015+P012039
BL0110023	persons 50 to 54 yr	50 to 54 years	P012016+P012040
BL0110024	persons 55 to 59 yr	55 to 59 years	P012017+P012041
BL0110025	persons 60 and 61 yr	60 and 61 years	P012018+P012042
BL0110026	persons 62 to 64 yr	62 to 64 years	P012019+P012043
BL0110027	persons 65 to 69 yr	65 and 66 years+67 to 69 years	P012020+P012044+P012021+P012045
BL0110028	persons 70 to 74 yr	70 to 74 years	P012022+P012046
BL0110029	persons 75 to 79 yr	75 to 79 years	P012023+P012047
BL0110030	persons 80 to 84 yr	80 to 84 years	P012024+P012048
BL0110031	persons 85 yr or older	85 years and over	P012025+P012049

APPENDIX B – Biosolids and Groundwater Risk Screening Tool (BGRST) User Manual

1. After unzipping Copy the 3MRA folder in the C directory.
2. To invoke the modeling system the user enters the C:/3MRA Folder. Scroll through to find SUI.exe. Click on SUI.exe (Figure A - 1).
3. Once the interface opens, Click on the File menu, then Click Open (Figure A - 2 and Figure A - 3). Now you should see “Open System Configuration File”.
4. Select HDprdex1.ssf by a click and then click Open as shown in Figure A - 4. If HDprdex1.ssf is not seen, then browse through to find the HDprdex1.ssf in C:/3MRA/ssf directory.
5. Select a Site from the list of 28 sites in the Site ID list box based on proximity to your site (Use Site Name list box as a guide). Then select one chemical from the Regulated Pollutant List-Box.
6. Input all the values in the text boxes (make sure to enter all or use default button to populate). By clicking “Use Default” button a default value will be populated. Then, click the Start Button to start the simulation. The model will run and provide a message at the end of run saying if the Hazard Quotient (HQ) value is less than 1 or greater than 1. Currently the model is limited in terms of information with regards to estimating excess cancer risks because of the non-availability of cancer slope factors for the water ingestion pathway.

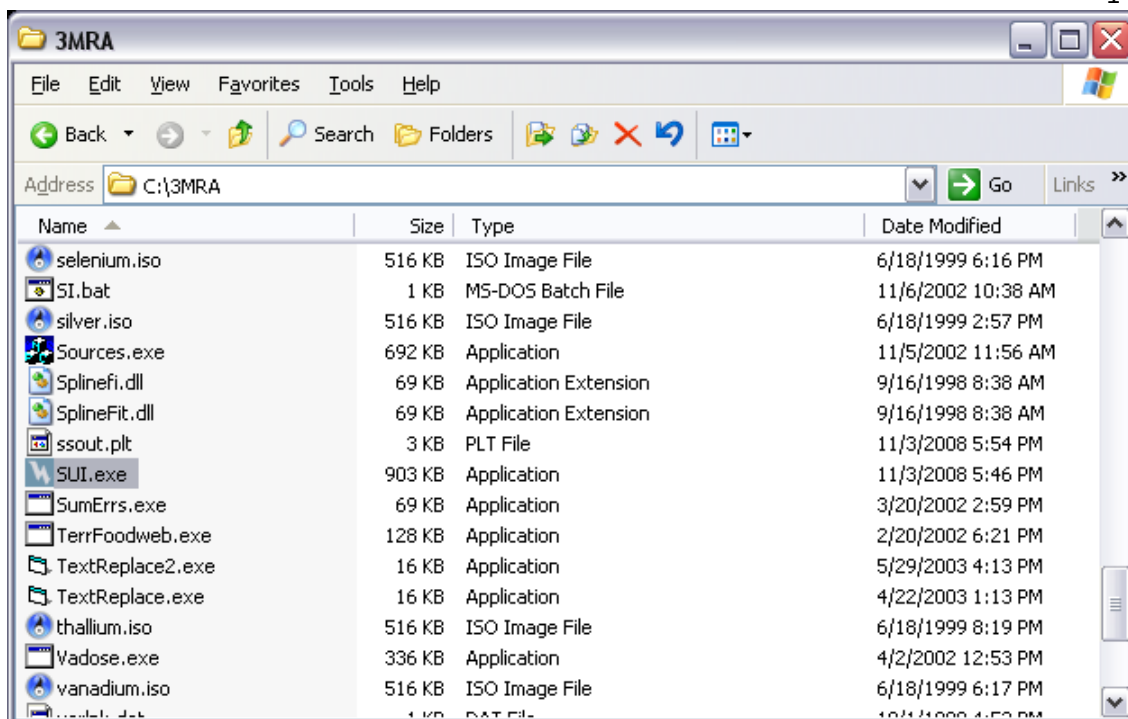


Figure A - 1. Screenshot of 3MRA directory

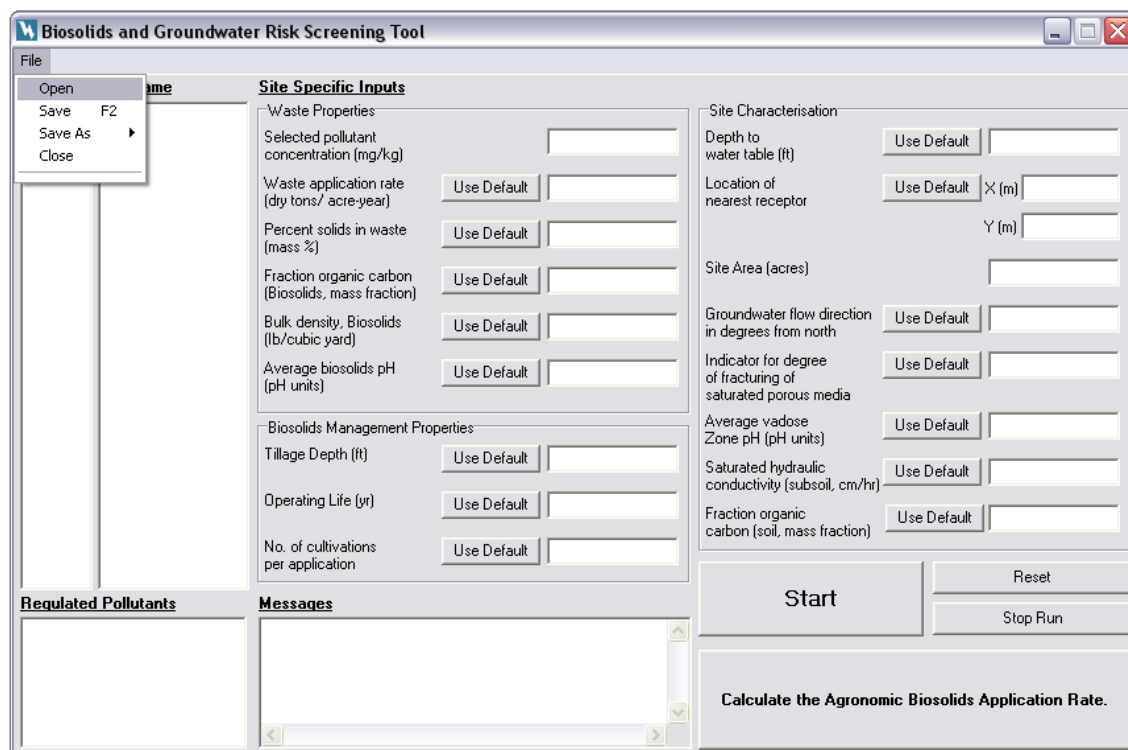


Figure A - 2. File Open Menu from BGRST user interface

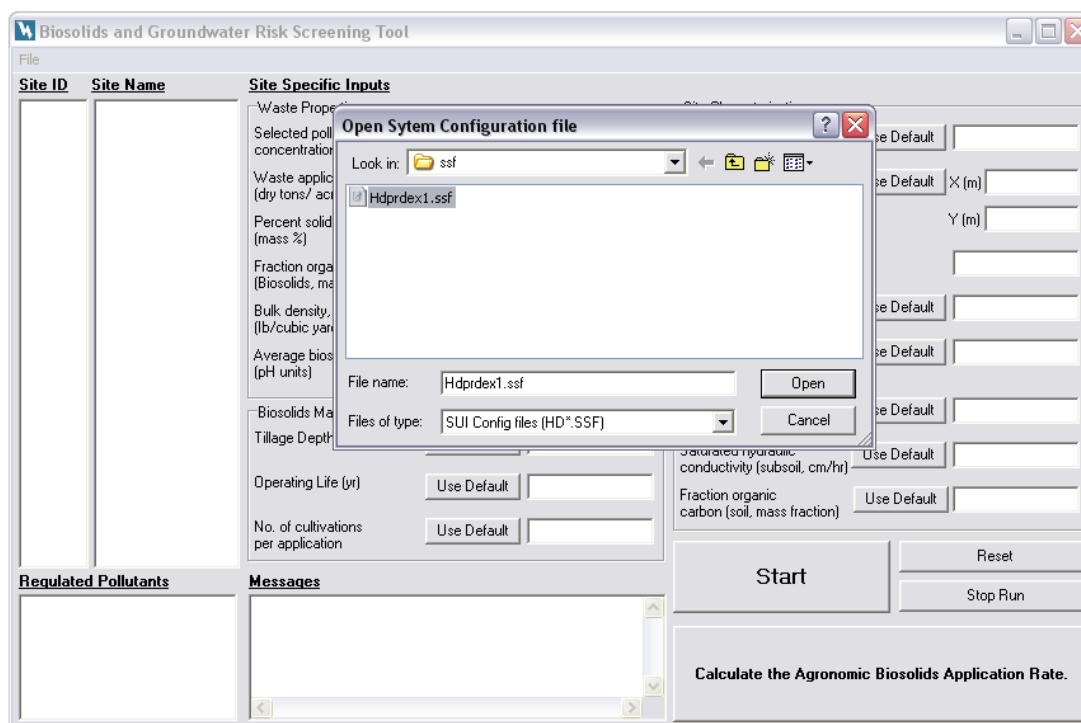


Figure A - 3. Selecting the header file to populate site options

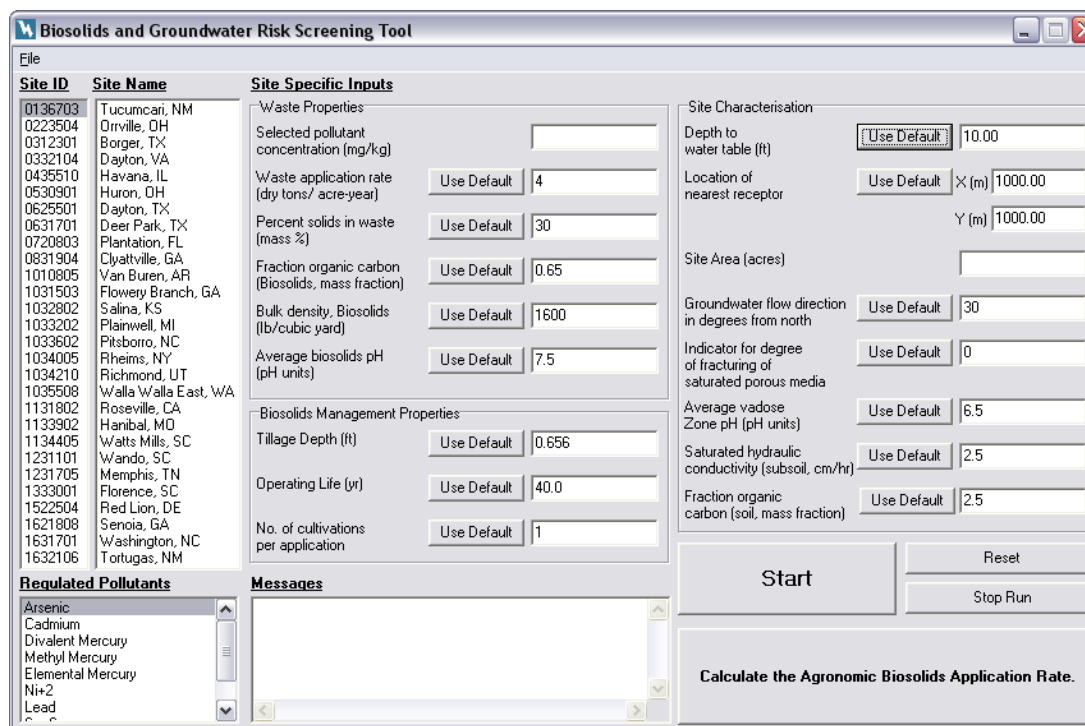


Figure A - 4. Populated user interface for BGRST

APPENDIX C – HQ from Drinking Impaired Groundwater

Three fully characterized sites from 3MRA model were selected to simulate a scenario that results in groundwater impairment from biosolids management practices at sites that are in the same Level IV ecoregion to the sites of the participating facilities. The sites selected are located in Virginia, Georgia and Washington. The Hazard Quotient (HQ) values for As, Cd, Ni, Se and Zn, contaminants regulated in Part 503, were evaluated at 1X, 2X, 5X, and 10X times the ceiling concentration for the water ingestion exposure pathway. The other regulated contaminants could not be evaluated as they do not have the reference dose (RfD) values for the water ingestion pathway. The HQ values for all the three sites for the various scenarios are listed in NMRW means No Mass Reaches the Water table.

C1. Site in Virginia

Scenario 1: Variable Contaminant Concentration and Biosolids Application Rate

- Depth to water table (m): 1.0
- Location of receptor and well: X (m): 1000, Y (m): 1000
- Site Area (m²): 40470 (10 acres)
- Number of cultivations per applications: 1

Table C - 1. Application rate (4 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	5.25e-9	5.31e-9	6.88e-8	6.58e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 2. Application rate (8 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	6.80e-10	3.07e-8
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	1.87e-7	1.87e-7	3.37e-6	7.3e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 3. Application rate (20 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.6e-7	1.15e-6	5.06e-6	1.22e-5
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	5.05e-6	2.02e-5	1.04e-5	4.58e-4
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 4. Application rate (40 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	2.63e-6	8.59e-6	2.4e-5	5.1e-5
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	1.34e-9	4.2e-9	1.26e-8	2.71e-8
Selenium	5.38e-5	2.22e-4	1.21e-3	6.63e-3
Zinc	NMRW	NMRW	1.67e-10	6.53e-10

Scenario 2: Variable Contaminant Concentration and Depth to Water Table

- Application rate (tons per acre): 4

Table C - 5. Depth to water table (m): 0.5 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	3.74e-8	2.23e-7	2.27e-7	6.54e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 6. Depth to water table (m): 2.0 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	3.74e-8	2.23e-7	2.27e-7	6.54e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 7. Depth to water table (m): 5.0 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	NMRW	NMRW	NMRW	NMRW
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 8. Depth to water table (m): 10.0 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	NMRW	NMRW	NMRW	NMRW
Zinc	NMRW	NMRW	NMRW	NMRW

Scenario 3: Variable Contaminant Concentration and Distance of Well

- Depth to water table (m): 1.0

Table C - 9. Application rate (400 tons per acre) - 200m from the boundary of the site

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	6.07	12.14	30.34	60.69
Cadmium	8.62e-1	1.72	4.31	8.62
Nickel	1.58	3.17	7.92	15.84
Selenium	24.82	49.64	124.09	248.19
Zinc	1.26e-1	2.53e-1	6.33e-1	1.27

Table C - 10. Application rate (200 tons per acre) - 500m from the boundary of the site

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.54e-2	3.73e-2	1.05e-1	2.02e-1
Cadmium	8.07e-4	1.38e-3	4.35e-3	9.94e-3
Nickel	2.21e-3	2.5e-3	8.72e-3	1.99e-2
Selenium	1.29e-1	2.52e-1	6.61e-1	1.28
Zinc	1.39e-4	2.25e-4	5.81e-4	1.39e-3

C2. Site in Washington:

Scenario 1: Variable Contaminant Concentration and Biosolids Application Rate

- Depth to water table (m): 3.048
- Location of receptor: X (m): 1000, Y (m): 1000
- Site Area (m²): (50 acres)
- Number of cultivations per applications: 1
- Groundwater class: Bedded sedimentary rock

Table C - 11. Application rate (4 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	3.47e-8	5.71e-8
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	2.3e-8	1.59e-7	6.35e-7	3.16e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 12. Application rate (8 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	1.3e-8	1.44e-7	1.42e-6
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	7.76e-8	6.15e-7	4.64e-7	1.16e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 13. Application rate (20 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.26e-8	1.23e-6	9.96e-7	2.58e-6
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	1.2e-8	1.07e-7	3.81e-7	7.91e-7
Selenium	5.59e-7	6.21e-7	2.57e-6	5.26e-6
Zinc	NMRW	2.89e-11	6.28e-9	1.71e-8

Table C - 14. Application rate (40 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	3.47e-7	6.84e-7	2.66e-6	1.06e-5
Cadmium	1.38e-8	1.37e-8	2.37e-8	3.03e-7
Nickel	3.8e-7	7.17e-7	1.13e-6	1.47e-6
Selenium	1.5e-6	1.04e-5	7.0e-6	4.74e-5
Zinc	4.52e-10	2.07e-8	4.3e-8	1.44e-8

Scenario 2: Variable Contaminant Concentration and Depth to Water Table

- Application rate (tons per acre): 4
- Solid (mass percent): 40%
- Location of receptor: X (m): 1000, Y (m): 1000
- Tillage depth (m): 0.2
- Site Area (m²): (50 acres)
- Operating Life (years): 40
- Number of cultivations per applications: 1
- Groundwater class: Bedded sedimentary rock

Table C - 15. Depth to water table (m): 0.5 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	6.1e-8	2.64e-7
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	8.48e-8	5.37e-7	9.16e-6	2.72e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 16. Depth to water table (m): 2 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	1.77e-7
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	5.41e-8	5.43e-8	5.17e-7	8.76e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 17. Depth to water table (m): 5 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	1.64e-8	5.85e-8	5.83e-8	3.55e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 18. Depth to water table (m): 10 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	1.64e-8	5.85e-8	5.83e-8	3.55e-7
Zinc	NMRW	NMRW	NMRW	NMRW

Scenario 3: Variable Contaminant Concentration and Distance of Well

- Depth to water table (m): 1.0
- Site Area (sq .m): (50 acres)
- Number of cultivations per applications: 1
- Groundwater class: Bedded sedimentary rock

Table C - 19. Application rate (400 tons per acre) - 200m from the boundary of the site

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	4.96	9.92	28.78	59.60
Cadmium	9.07e-1	1.01	3.45	9.07
Nickel	1.23	1.98	5.67	14.47
Selenium	21.31	37.23	119.76	223.09
Zinc	1.33e-1	3.32e-1	4.17e-1	1.33

Table C - 20. Application rate (200 tons per acre) - 500m from the boundary of the site

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.33e-3	2.69e-3	6.54e-3	1.17e-2
Cadmium	1.59e-4	2.84e-5	9.44e-4	1.94e-3
Nickel	3.02e-4	3.31e-4	8.74e-4	1.48e-3
Selenium	4.01e-3	9.04e-3	2.02e-2	3.99e-2
Zinc	2.44e-5	3.35e-5	5.79e-5	9.98e-5

C3. Site in Georgia

Scenario 1: Variable Contaminant Concentration and Biosolids Application Rate

- Depth to water table (m): 1.0
- Location of receptor: X (m): 1000, Y (m): 1000
- Site Area (m²): (100 acres)
- Number of cultivations per applications: 1

Table C - 21. Application rate (4 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	1.64e-7	7.34e-7
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	1.27e-7	1.02e-6	1.5e-6	4.18e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 22. Application rate (8 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	2e-7	8.78e-7	2.52e-6
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	4.19e-6	1.3e-5	4.49e-5	1.38e-4
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 23. Application rate (20 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	4.9e-7	1.94e-6	6.69e-6	9.5e-6
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	3.33e-9	2.2e-8
Selenium	1.45e-5	5.5e-5	1.87e-4	1.22e-3
Zinc	NMRW	8.31e-13	6.16e-11	1.31e-7

Table C - 24. Application rate (40 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.85e-6	4.75e-6	1.5e-5	3.98e-5
Cadmium	NMRW	NMRW	7.8e-11	1.79e-9
Nickel	1.4e-7	3.65e-7	1.03e-6	1.78e-6
Selenium	6.2e-5	1.81e-4	1.25e-3	3.03e-3
Zinc	3.57e-10	1.53e-9	7.45e-9	3.39e-8

Scenario 2: Variable Contaminant Concentration and Depth to Water Table

- Application rate: (4 tons per acre)
- Location of receptor: X (m): 1000, Y (m): 1000
- Site Area (sq .m): (50 acres)
- Number of cultivations per applications: 1
- Groundwater class: Bedded sedimentary rock

Table C - 25. Depth to water table (m): 0.5 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	4.41e-8	2.11e-7	5.76e-7
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	6.14e-11	2.56e-10
Selenium	1.08e-6	2.58e-6	1.61e-5	3.26e-5
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 26. Depth to water table (m): 2 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	4.52e-7
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	2.89e-7	2.89e-7	3.07e-6	9.22e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 27. Depth to water table (m): 5 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	1.24e-7	7.11e-7	7.12e-7	2.53e-6
Zinc	NMRW	NMRW	NMRW	NMRW

Table C - 28. Depth to water table (m): 10 m

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	NMRW	NMRW	NMRW	NMRW
Cadmium	NMRW	NMRW	NMRW	NMRW
Nickel	NMRW	NMRW	NMRW	NMRW
Selenium	NMRW	NMRW	NMRW	NMRW
Zinc	NMRW	NMRW	NMRW	NMRW

Scenario 3: Variable Contaminant Concentration and Distance of Well

- Depth to water table (m): 1.0
- Site Area (m²): (100 acres)
- Number of cultivations per applications: 1

Table C - 29. Application rate (tons per sq. m-yr): 0.269 (400 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	6.79	13.53	34.00	68.00
Cadmium	8.00e-1	1.71	4.61	9.14
Nickel	1.64	3.34	8.69	17.38
Selenium	32.4	64.8	162.00	324.00
Zinc	1.33e-1	2.58e-1	6.79e-1	1.44

Table C - 30. Application rate (tons per sq. m-yr): 0.135 (200 tons per acre)

Regulated Contaminant	Ceiling Concentration 1X	Ceiling Concentration 2X	Ceiling Concentration 5X	Ceiling Concentration 10X
Arsenic	1.69e-2	8.21e-2	3.10e-1	4.43e-1
Cadmium	1.32e-4	2.31e-3	3.34e-3	1.89e-2
Nickel	5.67e-2	5.73e-3	1.02e-2	6.01e-2
Selenium	2.43e-1	3.67e-1	1.01	2.23
Zinc	1.79e-4	3.11e-4	8.32e-4	8.45e-3

APPENDIX D – Cancer and Non-cancer Risk from Four Pathways

Table D - 1. Cancer and non-cancer risk for the AOI for As from four pathways of exposure***

Pathways	Risk type	Infant	Child 2	Child 3	Child 4	Adults
Ring 1						
Air inhalation	Cancer risk	0	3.5E-14	3.5E-14	6.8E-14	1.7E-14
	Non-cancer risk	NA*	NA*	NA*	NA*	NA*
Soil ingestion	Cancer risk	0	1.2E-06	1.6E-06	4.7E-07	3.6E-06
	Non-cancer risk	0	0.046	0.105	0.028	0.180
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA**	NA**	NA**	0	0
	Non-cancer risk	NA**	NA**	NA**	0	0
Ring 2						
Air inhalation	Cancer risk	0	8.1E-14	3.5E-14	6.8E-14	1.7E-14
	Non-cancer risk	NA*	NA*	NA*	NA*	NA*
Soil ingestion	Cancer risk	0	9.7E-07	1.6E-06	4.9E-07	3.6E-06
	Non-cancer risk	0	0.046	0.105	0.028	0.180
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA**	NA**	NA**	0	0
	Non-cancer risk	NA**	NA**	NA**	0	0
Ring 3						
Air inhalation	Cancer risk	0	8.1E-14	3.5E-14	6.8E-14	1.7E-14
	Non-cancer risk	NA*	NA*	NA*	NA*	NA*
Soil ingestion	Cancer risk	0	9.7E-07	1.6E-06	4.9E-07	3.6E-06
	Non-cancer risk	0	0.046	0.105	0.028	0.180
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA**	NA**	NA**	0	0
	Non-cancer risk	NA**	NA**	NA**	0	0

Table D - 2. Cancer and non-cancer risk for the AOI for Cd from four pathways of exposure***

Pathways	Risk type	Infant	Child 2	Child 3	Child 4	Adults
Ring 1						
Air inhalation	Cancer risk	0	6.21E-15	6.23E-15	9.22E-15	1.85E-15
	Non-cancer risk	NA*	NA*	NA*	NA*	NA*
Soil ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0.0041064 33	0.0094197 09	0.0025047 57	0.0162121 97
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA*	NA**	NA**	0	0
	Non-cancer risk	NA*	NA**	NA**	0	0
Ring 2						
Air inhalation	Cancer risk		2.12E-14	6.23E-15	9.22E-15	1.85E-15
	Non-cancer risk	NA	NA	NA	NA	NA
Soil ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk		0.0041064 33	0.0094197 09	0.0025047 57	0.0162121 97
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA*	NA**	NA**	0	0
	Non-cancer risk	NA*	NA**	NA**	0	0
Ring 3						
Air inhalation	Cancer risk	0	2.12E-14	6.23E-15	9.22E-15	1.85E-15
	Non-cancer risk	NA	NA	NA	NA	NA
Soil ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk		0.0041064 33	0.0025047 57	0.0025047 57	0.0162121 97
Water ingestion	Cancer risk	0	0	0	0	0
	Non-cancer risk	0	0	0	0	0
Inhalation from showering	Cancer risk	NA*	NA**	NA**	0	0
	Non-cancer risk	NA*	NA**	NA**	0	0

NA* Data for non-cancer related illness from inhalation is not available, therefore this pathway is not applicable.

NA** - These cohorts are assumed to bathe.

*** - The risk evaluated is the outcome of the background soil concentration and the biosolids land application practice.

Infant – Less than 1 year of age

Child 2 – Between 1 and 5 years of age

Child 3 – Between 6 and 11 years of age

Child 4 – Between 12 and 19 years of age

Adults – Greater than 20 years of age

APPENDIX E – As, Cd, B(a)P and DEHP Concentration in Food

Food	Reference
Rice	Meharg and Rahman (2002)
Shrimp	Schoof et al. (1999)
Cod	Schoof et al. (1999)
Offal	Galal-Gorchev (1993)
Shellfish	Galal-Gorchev (1993)
Lettuce	Müller and Anke (1994)
Onion shallot	Müller and Anke (1994)
Dill	Müller and Anke (1994)
Baby food	Petersen and Breindahl (2000)
Milk cream	Castle et al. (1990)
Curry paste	Fankhauser-Noti et al. (2006)
Tomato paste	Fankhauser-Noti et al. (2006)
Pesto	Fankhauser-Noti et al. (2006)
Grilled/barbecued chicken	Kazerouni et al. (2001)
Tea leaves	Lintas et al. (1979)
Hamburger cooked	Lintas et al. (1979)
Liquid smoke flavor (food additive)	Yabiku et al. (1993)

APPENDIX F – Chemical Properties

Chemical Property	Arsenic	Cadmium	B(a)P	DEHP	Distribution
Thermodynamic Properties (Organic chemicals)					
Solubility	NA	NA	1.62E-03	3.40E-01	Constant
Air diffusivity	0	0	4.30E-02	3.51E-02	Constant
Water diffusivity	1.00E-04 - 1.00E-02	1.00E-04 - 1.00E-02	9.00E-06	3.66E-06	Uniform
Partition Coefficients (organic Chemicals)					
Henry's law constant	NA	NA	1.13E-06	1.02E-07	Constant
Soil-water partition coefficient	NA	NA	968,774	111,123	NA
Degradation Constant (Organic Chemicals)					
Hydrolysis rates	NA	NA			
Aerobic biodegradation rates	NA	NA	0.0027	0.0205	Constant (mean)
Anaerobic biodegradation rates	NA	NA	NA	NA	NA
Partition Coefficients (metals)					
Partition coefficients (Biosolids, soil and sediment)	1.6 - 15962.1	1.0 - 80000	NA	NA	Uniform
NA – Not applicable					

CURRICULUM VITAE

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EDUCATION

Utah State University, Logan, UT

- Doctor of Philosophy in Civil and Environmental Engineering July 14
- Master of Science in Civil and Environmental Engineering August 07

Visvesvaraya National Institute of Technology, Nagpur, India

- Bachelor of Engineering in Civil Engineering May 04

CERTIFICATION

- Engineer in Training December 09
- Laboratory Safety Training (Hazardous waste management, fire safety) May 10
- CUAHSI Water Data Center - Utah State University Software Carpentry July 13
- Boot Camp
- Sediment Transport for Stream Assessment and Design Workshop July 13 – August 13
- Advanced SWAT training January 14

PROPOSALS

Coupled human-biophysical framework to predict conservation effectiveness

- Proposal accepted (\$120 000).

Nutrient Loading, Transformations, and Management in Irrigated Agro-ecosystems

- Co-authored \$500 000 grant from United States Department of Agriculture.

Chemical contaminant risk assessment for sustainable groundwater protection at biosolids land application sites

- Authored proposal for extending the project; received funding from WERF.

Development of biosolids risk indicator and characterization system.

- Co-authored proposal to evaluate risk associated with biosolids land application practice.

EXPERIENCE

Area: Sediment management and mitigation

Belmont Hydrology and Fine Sediment Laboratory, Logan, UT

November 12 - Present

Characterizing non-field near-channel sediment sources using SWAT model and validating predictions using radiogenic tracers (¹⁰Be, ²¹⁰Pb and ¹³⁷Cs) (Funding Agency: National Science Foundation)

- Built SWAT model for the Le Sueur River Basin and Greater Blue Earth River Basin.

- Assessed the impact of drain tiles and agricultural management practices on flow and sediment transport.
- Validate predictions using radiogenic tracers.
- Develop conceptual and mathematical model to include near channel and in channel processes in SWAT model.

GeoNet model for Minnesota River Basin (Funding Agency: National Science Foundation)

- Developed conceptual model within the GeoNet 2.0 framework to locate banks based on the derivative of terrain slope.

Area: Conceptual and Numeric Fate & Transport Modeling

Utah Water Research Laboratory, Logan, UT

August 04 - Present

Chemical contaminant risk assessment for sustainable groundwater protection at biosolids land application sites

(PhD; Funding Agency: Water Environment Research Foundation)

- Modified EPA's Multimedia, Multi-pathway, Multi-receptor Exposure and Risk Assessment (3MRA) model and developed **Biosolids and Groundwater Risk Screening Tool (BGRST)** software to compute hazard from drinking groundwater impaired with seven constituents of concern from CERCLA priority list (Arsenic, Cadmium, Nickel, Selenium, Zinc, Bis (2-ethylhexyl) phthalate and Benzo (a) pyrene) at biosolids land application sites.
- Developed and incorporated plant uptake and irrigation components in the 3MRA model.

iUtah Coupled Human-Natural System Interaction (Funding Agency: National Science Foundation)

- Built an inventory of studies describing the utility of models in Cache Valley pertaining to water and climate.
- Developed an Agent Based Model (ABM) that coupled with QUAL2Kw to model water use change due to changes in water quality. Agents include agricultural and urban water users and water master.
- Helped MS and PhD students with conceptual model development and code development.

Phosphorus transport from land applied biosolids (Funding Agency: Utah Water Research Laboratory)

- Assisted with collecting data required for the modeling effort.
- Assisted with Modeling P transport from land applied biosolids using EPIC.
- Assisted with the developed Phosphorus Site Index (PSI) for biosolids land application sites in Utah.

Effect of heavy metals from flue gas in algae growth, biodiesel production and metal distribution

- Conceptual model development of an Arsenic bio-remediation experiment (sample preparation for ICP-MS & AAS).
- Assisted with the modeling efforts involving metal internalization and adsorption in a photobioreactor.

Vulnerability of shallow aquifers of the conterminous United States to NO_3^- : Assessment of methodologies (MS; Funding Agency: Utah Water Research Laboratory)

- Developed aquifer vulnerability model based on modified DRASTIC model and ordinal logistic regression.
- Compared model performance with respect to historic NO_3^- concentration data in drinking water wells.
- Automated repetitive and tedious jobs using Model Builder tool in ArcGIS.

Comparative Analysis of Orographic Effects for Estimating Peak Flows (MS; Funding Agency: Utah Water Research Laboratory)

- Improved methods for estimating peak flows (for the safe and economic design of drainage structures).

Indian Institute of Science, Bangalore, India

May 04 - August 04

- Assisted with the developed of an integrated ground and surface water model for the Gundal Watershed (India).
- Validated the use of **Soil and Water Assessment Tool (SWAT)** model to Gundal Watershed.

Visvesvaraya National Institute of Technology, Nagpur, India

September 03 - March 04

- Analysis of gradually varied flow profiles using artificial neural networks (ANN) in MATLAB.

Indian Institute of Technology, Madras, India

June 03 - July 03

- Analyzed traffic volumes for adequacy of pavement capacity.

Area: Human Health Risk Assessments

Utah Water Research Laboratory, Logan, UT

August 07 - Present

Chemical contaminant risk assessment for sustainable groundwater protection at biosolids land application sites

(PhD; Funding Agency: Water Environment Research Foundation)

- Analyzed the effectiveness of biosolids regulations and BMPs. Performed site-based human health risk assessment for biosolids land application (Contaminant fate and transport modeling in a multimedia setting using modified 3MRA).
- Worked with large datasets using relational databases and other applications. Used legacy software (required conversion from older to new formats). Data categories include: national databases such as soils data (STATSGO, SSURGO), surface air data (e.g., SAMSON, TD 3240 and DS3240), upper air data (DSI 6301 twice daily mixing height data), water quality (NAWQA), health district data and wastewater treatment facility data.
- Access 97 database used by 3MRA was modified to account for changes made to the software. Modifications include SQL queries and designing the interface to access and update data.
- Co-conducted and provided technical updates for teleconferences (10 large POTW's, US EPA, USGS and Utah DEQ).
- Designed national surveys to gather critical information required for modeling (from generation to disposal of biosolids) from POTW's, health districts and biosolids land application companies.

Microbial risk assessment for sustainable protection at biosolids land application sites (Funding Agency: Water Environment Research Foundation)

- Reviewed microbial risk assessment methodology and provided recommendations to improve model.
- Co-conducted teleconferences involving large POTW's, regulators from state and federal agencies from US and Canada.

Area: Field Investigations

Utah Water Research Laboratory, Logan, UT

July 08 - Present

Impact of beaver introduction in native fish habitat (Funding Agency: Utah Division of Wildlife Resources)

- Identified ideal locations for installing pressure transducers and temperature probes.
- Installed pressure transducers for continuous stage measurement at 5 minutes intervals.
- Installed temperature probes for continuous temperature logging in a beaver pond (Spatial and temporal variation).

Establishing stage-discharge relationship in multiple locations at Boulder Creek, Boulder Mountain, Utah. (Funding Agency: Garkane Energy)

- Collected discharge data at Boulder Creek.

Algal biomass production for use in Pyrolytic Oils and biodiesel production

- Assisted with maintenance of industrial scale algal photobioreactors.
- Harvested and concentrated algae using Cross Flow Unit and centrifugation.

Effect of beaver dams on temperature and flow in streams (Funding Agency: Utah Water Research Laboratory)

- Collected topographic and bathymetry data at approximately 20 cm resolution using GPS.
- Performed reconnaissance for ideal temperature sensor installation locations and installed temperature probes.
- Measured discharge data.
- Collected depth to water and well depth data and performed necessary maintenance of the monitoring well.

Minimum Flow Requirements for the San Rafael River. (Funding Agency: Emery Water Conservancy District)

- Collected topographic and bathymetry data using engineer's level.
- Collected discharge data using Marsh-McBirney Flo-Mate.

Seepage evaluations in Cache Valley Irrigation System (Funding Agency: Utah Water Research Laboratory)

- Discharge measurement using Acoustic Doppler velocity meter.
- Assisted with the GIS visualization efforts.

Coursework related field and lab experience

- Performed water sampling in the Logan River at various depths using Kemmerer sampler.

- Collected samples to assess hardness, alkalinity, turbidity, TOC, total N, ammonia, nitrate, nitrite, Kjeldahl N, total P, total reactive P, dissolved reactive P, dissolved condensed P, total dissolved P, total and dissolved metals.
- Performed sample filtration in the field for dissolved reactive P, dissolved condensed P, total dissolved P and all dissolved metals in order to avoid changes on samples speciation during trip and storage.
- Measured dissolved oxygen in the field by Winkler method using the LaMotte field test kit and compared results with measurements taken by YSI dissolved oxygen probe.
- Used YSI 63 and Hydrolab Datasonde 4A to measure pH, conductivity, temperature and salinity in the Logan River.

Area: Data Visualization

Utah Water Research Laboratory, Logan, UT

May 12 – August 12

Chemical contaminant risk assessment for sustainable groundwater protection at biosolids land application sites

(PhD; Funding Agency: Water Environment Research Foundation)

- Extensively used ArcGIS software for data extraction, visualization and computation.

Visualization of temperature time series data in a beaver pond using MATLAB

- Developed video using MATLAB to visualize spatial and temporal changes in temperature for a beaver pond.
- Developed an algorithm to slice volume using MATLAB to model changes in temperature in a beaver pond.

National Scenic Byways, Logan, UT

May 08 – August 08

National Scenic Byways map creation project

- Wrote macros to automate processes using VBA in ArcGIS.
- Prepared national scenic byway maps using ArcGIS and used Photoshop for quality online map display.

Area: Software Development

Utah Water Research Laboratory, Logan, UT

January 10 - December 11

Regulatory Compliance software development

- Designed and developed Biosolids Land Application Support Tool (BLAST) software (using C# and SQLite) that allows residuals stakeholders (e.g. land application firms and POTW's) to evaluate, manage and report the regulatory compliance information associated with biosolids beneficial use.
- Conceptualized and designed BLAST database.
- Designed and developed Biosolids Risk Indicator Characterization System software (using Borland C++, Visual C++ and FORTRAN) by adapting US EPA's 3MRA framework, allowing the user to conduct a cumulative characterization of the human health risks associated with biosolids land application from different pathways.
- Managed software programmers, environmental engineers and a marketing team.

Area: Engineering Design

M2 Group, Inc., Mesa, AZ

January 06 - December 06

Hydrologic and hydraulic modeling: Storm water management

- Designed swales for land development projects.
- Designed channels, culverts, drop structures, catch basins, infiltration basins, dry and wet detention ponds for managing storm water in new and existing land development projects.
- Delineated and analyzed floodplains and flows, respectively, and designed structures for flood routing.

Site Layout and Engineering

- Performed earthwork analysis and lot grading using Autodesk Map and Autodesk Land.
- Designed water and sewer systems with EPANET and sewerCAD, respectively.
- Authored technical reports (water, sewer, grading and drainage reports).

Area: Teaching Experience

Utah State University, Logan, UT

August 04 - Present

- Taught Small watershed hydrology (lab and lecture)
- Graded assignments and projects for undergraduate course in engineering economics.
- Tutored managerial economics, intermediate microeconomics, physics I, physics II and intermediate calculus
- Assisted with graduate level biosolids engineering and management class.

COMPUTER SKILLS

Scientific Applications:

- Risk Assessment: US EPA 3MRA and submodels (17 different models)
- Surface water:
Contaminant Transport: SWAT, CropMan, WinEPIC and Reasonable Potential Analysis (RPA), QUAL2Kw and GeoNet
Hydrology: WMS and HEC-1
Hydraulics: StormCAD, Culvert Master, Flow Master, SewerCAD, EPANET and HEC-RAS
- Groundwater: MODFLOW, MINTEQA2 and NLEAP

Technical Drawing and Mapping: Autodesk Map, Autodesk Land, ArcGIS, MapWindow and Surfer

Programming: MATLAB, Visual Basic, C, C++, C# and SQL

Statistics: R and MINITAB

Database and other tools: MS Access, SQL Server, SQLite and MS Office

LANGUAGES

English, Hindi, Tamil, Kannada, Telugu, Sanskrit (Read and write) and Spanish (Novice)

LABORATORY EQUIPMENT

- Spectrophotometer, Ion Chromatograph and familiarity with ICP-MS and AA and pH meters
- MARSH-McBIRNEY flow meter, Acoustic Doppler Velocimeter, YSI 63 (pH, Conductivity, Temperature & Salinity Meter) and Hydrolab Datasonde 4A (pH, Conductivity, Temperature & Salinity Meter), TidbiT v2 Water Temperature Data Logger, Solinst® 189 electronic well sounder: Model 101, Cross Flow Unit, Level® TROLL 300, and BaroTROLL®

JOURNAL ARTICLES

- Belmont, P., Willenbring, J. K., Schotttler, S. P., Marquar, J., **Kumarasamy, K.**, Hemmis, J. (2014). Toward generalizable sediment fingerprinting with tracers that are conservative and non-conservative over sediment routing timescales. *Journal of Soils and Sediments*. 1-14.
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, A. Hais, and M. D. Schmitz (2013). Impact of Biosolids Recycling on Groundwater Resources. *Water Environment Research*. Vol. 85 (11) 2141-2146 (6).
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, A. Hais, and M. D. Schmitz (2013). Protecting Groundwater Resources at Biosolids Recycling Sites. *Journal of Environmental Quality*. Vol. 10 2134-2139.
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, A. Hais, and M. D. Schmitz (2012). Groundwater quality protection at biosolids land application sites. *Water Research*. Vol. 46 (18) 5963-5969.
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, A. Hais, and M. D. Schmitz (2011). Are Part 503's pollutant limits still valid? New modeling program indicates effect of land-applied biosolids on nearby groundwater. *Biosolids Technical Bulletin*, WEF, Vol. 17 (5)11:13.
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, A. Hais, and M. D. Schmitz (2011). Characterizing Human Health Risks Associated with Biosolids Land Application Practices. *Proceedings of the Water Environment Federation, Residuals and Biosolids 2011*, pp. 187-196(10).
- **Kumarasamy K.**, M. McFarland, and K. Bhayani (2011). Simulating our way to a greener future: Sustainable Residual Management. *Utah Engineers Council Journal*, 35-36.

REPORTS AND POSTERS

- **Kumarasamy K.**, and McFarland M. J. (2014). What happens to Arsenic and Cadmium from biosolids following land application? W2170 Biosolids Conference, Chicago, IL. June 30th 2014.
- **Kumarasamy K.**, and McFarland M. J. (2013). What happens to Arsenic and Cadmium from biosolids following land application? WEAU midyear conference, West Valley City, UT. November 12th 2013.
- **Kumarasamy K.**, and Belmont P. (2013). Incorporating channel dynamics into SWAT: A case study in the Le Sueur watershed. REACH 2013 Annual PI Retreat, Mankato, MN. August 12th – August 14th 2013.
- McFarland M. J., **K. Kumarasamy**, M. D. Schmitz (2011). Risk Characterization Using Modified 3MRA at Biosolids Land Application Sites. *Mineral Lease Fund Report*. Section 4-31.
- McFarland M. J., **K. Kumarasamy**, R. B. Brobst, and M. D. Schmitz (2010). Evaluation of Best Management Practices for sustainable groundwater protection at biosolids land application sites. WERF, 05-CTS-2T, 2010.
- Grenney, W. J., **K. Kumarasamy**, R. C. Nataraj (2004). Water Resources Planning and Management Project for the State of Utah. *Mineral Lease Fund Report*. Section 9-4.

PRESENTATIONS

- Presenter: **2nd place** in the Graduate Student Symposium 2010. Risk characterization of biosolids land application practices using the risk characterization screening tool (RCST).
- Presenter WEAU conference 2009: Use of EPA's Multimedia, Multi-pathway, Multi-receptor Exposure and Risk Assessment (3MRA) technology to characterize biosolids land application.
- Presenter WEAU conference 2008: Use of the Multimedia, Multi-pathway, Multi-receptor Exposure and Risk Assessment (3MRA) model to assess risk from groundwater pollutants at biosolids land application sites.

LEADERSHIP/ SERVICE

- E-State: Helped with the organization and conductance of the filtration session activities for middle and high school students (2011 and 2013 years).
- Member of the review committee for the International Conference on "Assessment and Management of Water Resources", Indian Institute of Science, Bangalore, India.
- **Highest Award in Scouting given by the President of India.**

COMPETITION AND AWARDS

- WEAU design challenge 2014. Designed treated effluent conveyance system (Pump design, pipe line design and layout).
- RGS and UWRL Travel award (\$600) - 2014.
- Graduate symposium (2nd price) - \$100.